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# Review of quench simulations for the protection of LHC main dipole magnets

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#### **Summary**

The simulation program QUABER [1] allows studying the quench process of superconducting magnets for the LHC. The performance of the protection system of the LHC main dipole magnets was simulated under various parameter dependencies at different magnet excitation currents. This simulation study was motivated to complement measurement results in order to help preparing and understanding experiments of the quench propagation and magnet protection.

The influence of the quench propagation velocity and the time for a quench propagation between adjacent turns was studied. The different copper plating cycles of the quench heater strips were simulated. Experimental measurement results [2] were used to calibrate the input parameters. The performance of the protection system for various quench detection thresholds was investigated and different failure modes of the system were considered. The maximum voltages and values of the quench load are discussed.

The values given are obtained using conservatively chosen parameters. The quench back effect is modelled at high currents by quenching the entire inner layer at a certain time after the quench start. The temperature evaluation is based on adiabatic calculation.

The main results of the study can be summarised as follows:

- Realistic values for the quench propagation were used to determine adequate detection parameters, i.e., a quench propagation velocity of about 15-20 m/s at nominal current and a time for quenching adjacent turns of about 20-30 ms were set for nominal current. Heater delays of 30ms (high field heaters) and 50-60ms (low field heaters) were used. It was shown that the detection should not be exceed a threshold at 0.2V and a validation integration time of 5 to 10 ms.
- The high field heaters alone are sufficient to protect the magnet even when a conservative assumption for the quench starting in the inner layer is made (for nominal current, at lower current no quench of the inner layer is assumed). This study also demonstrated the importance of the quench propagating into the inner layer. When a quench in the inner layer is excluded, the quench load value reaches very high values independent from the heater strip configuration.

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- The turn on voltage of the power diode that is installed in parallel to each magnet is reached at any current even if the heaters fail, i.e., they are unable to provoke a quench a low magnet currents. The diode alone is able to protect the magnet up to a current of about 2.3kA. Above that value, quench heaters are required.
- The quench heater study includes the systematic investigation of different heater delays, failing of one or several heater strips, and different copper plating cycles. The copper plating cycle was found to have little influence on the protection. The voltages inside the magnet can reach values up to 1 kV due to scattering heater delays or failing quench heater channels. The model that allows asymmetric quenching of the magnet was also used to reproduce an accidental quench of the first six block 15m long prototype dipole magnet that is being tested at CERN.

# 1. Introduction

The main dipole magnets of the LHC will be protected by quench heaters that are fired after a quench detection of and parallel diodes. The firing of quench heaters ensures a more uniform distribution of the stored magnetic energy and the current bypasses the magnet and flows through the protection diode after the resistive voltage exceeds the turn on voltage of the diode.

The performance of the protection system for the MB dipole magnet relies on a number of different parameters [3]. Among these are the threshold detection voltage, used to trigger the protection system, and the heater delays that determine when quench heaters become effective after having been fired. The parameter studies described below are carried out to better understand experimental results and to improve the definition of the QUABER magnet models for future work. A comprehensive study was conducted to provide detailed cause-and-effect relationships between different magnet parameters. The calibrated simulation data on hot spot temperature, quench load, resistance developed, etc. was compared resulting from various scenarios.

The different simulation can be grouped as follows:

• *Model study*: Determine to what extent uncertainties in the following parameters affect the results from, and usability of, the QUABER model, as well as how measurement results from a real magnet may be affected because of these parameters:

turn-to-turn quench propagation delay quench propagation velocity RRR of copper matrix of the conductor copper plated and heated part lengths location of quench origin

- *Magnet current effects*: Qualif heater delays at various detection voltages and current levels, both for single magnets and series magnets. The resistance development, quench load and hot spot temperature is recorded. The main goal is to help determining acceptable threshold detection voltages.
- *Failures:* Determine the consequences of component failures on a magnet for various currents and conditions. This includes the failure of heaters placed in the high field region,

those placed in the low field region and the failure of the protection diode (current cannot bypass by flowing through the diode).

- *Heater study:* A comprehensive study of the interactions between the various heater delays, for both single and series magnets, is carried out to help determining the required detection level.
- *Aperture quenching asymmetries:* The effects of timing differences (scattering) between apertures of heater firings and of the complete heater firing failure of one aperture are examined.

# 2. MB dipole magnet simulation studies



As shown in the above cross section (Figure 1), the MB dipole magnet consists of two apertures, each possessing eight heaters stips. The HF "high field" heaters (strips 1) are located in the high field region of the magnet, whereas the LF "low field" heaters (strips 2) are in a low field region. In the majority of these studies, at time t = 0, the quench will be assumed to originate in the high field region of the outer layer (*quench origin 1*) [2]. QUABER simulates the propagation of the quench throughout the other turns of the magnet, taking into account the firings of the heaters. In these studies, the inner layers are quenched artificially at a time which is adjusted according to experimental results, allowing the effects of quench-back and time of inner layer quench to be emulated more accurately.

The results obtained from QUABER are the values of the hot spot temperature, quench load, resistance developed, current decay, maximum voltage and the time required to reach the maximum voltage. The temperatures in these simulations are calculated adiabatically, i.e. cooling effects are neglected. Figure 2 shows conversion charts between quench load, and resistivity versus temperature for the cables used in the magnet studies. Note that the magneto resistance is only significant at temperatures below 80 K, above which it is a function only of RRR and temperature.









Quench load vs. T for outer layer, RRR=130



T vs. rho for outer layer, RRR=130









The electrical layout of the MB dipole magnet is shown in Figure 3. For our studies, the quench begins at t = 0. After a given time (see Table 1), the switch opens across the extraction resistor and the power supply is switched off to emulate conditions in the actual



Figure 3

Variable	Description	Typical value
<i>b_m</i>	peak magnetic field	8.61335 T
cssdt	time at which voltage source is switched to 0 V	24.1 ms
ht_delay_high r	aperture 2 high field heater delay	54.1 ms
ht_delay_high_l	aperture 1 high field heater delay	54.1 ms
ht_delay_in1	aperture 1 time of inner layer quench	125.9 ms
ht_delay_in2	aperture 2 time of inner layer quench	125.9 ms
ht_delay_low_l	aperture 1 low field heater delay	75.9 ms
<i>ht_delay_low_r</i>	aperture 2 low field heater delay	75.9 ms
i0	nominal current	11796 A
len_cu	copper plated length of the heater strip cycle	40.0 cm
len_heat	heated length of the heater strip cycle	12.0 cm
ltot	total inductance for one magnet in the series	0.1074 H
quench_velocity	quench velocity at initial current	2000 cm/s
rex	external extraction resistance (single magnet)	20 mΩ
rex	external extraction resistance (magnet series)	150 mΩ
swdel	time after start of quench to switch in extraction resistor	24.1 ms
ttx	quench propagation between adjacent turns	30 ms

Table 1: Parameters studied

magnet. When the resistive voltage across the magnet reaches the turn-on voltage of protection diode (8.3 V is used at 1.8 K), current begins bypassing the magnet through the diode. Different parameters are studied using this model. See Table 1 for a short description of each. All times are measured from start of quench.

Constant parameters are set to the values in Table 1 unless otherwise noted. Cable parameters for the MB dipole magnet used in the simulation studies are shown below. The majority of simulations were conducted with RRR=180 and RRR=150, respectively (although as will soon be apparent, the inner layer RRR makes little difference for the quench performance).

Parameter	Outer layer	Inner layer
RRR	180, 130	200, 150, 100
Ratio Cu/NbTi	1.9	1.6
Copper area [cm*cm]	0.126083	0.153495
NbTi area [cm*cm]	0.066359	0.095934
Total cable width [cm]	0.173855	0.214005
Metal width [cm]	0.127445	0.168533
Total cable height [cm]	1.54	1.51
Total metal height [cm]	1.51	1.48

Table 2: Cable parameters

The QUABER setup for a single magnet is shown below. The quench begins at orig.ou1, and progresses through the other turns of the first aperture. Heater "heat.xxx" elements are fired after detection and their effects are felt by nearby turns not covered by heaters (the passive "pass.xxx" elements) according to the turn-to-turn propogation time *ttx*. The ghost element is included to satisfy QUABER's connection requirements [1] and has no effect on the electrical behaviour of the circuit. The inner layers of the magnet are quenched artificially using QUABER "heat.xxx" elements, whose quench times can be precisely controlled to model behaviour of actual magnets.

MB DIPOLE (SINGLE MAGNET) QUABER SETUP



### 2.1. Model study

#### 2.1.1. Accuracy

Many of the graphs presented in these studies present the quench load versus a certain parameter. The unit to be used for the quench load is the MIIT, or kA\*kA\*s, calculated by as follows:

$$MIIT = \int_0^\infty I^2 dt \text{ in units of } kA^*kA^*s$$
(1)

The starting time 0 stands for the start of the propagating quench. The accuracy of QUABER is limited by the time step of the simulations. At 0.2 V detection, nominal current, there is a 0.4 MIITS increase in quench load when the time step is increased from 5 ns to 30 ns, and a further increase of 0.3 MIITS when 50 ns is reached. The accuracy of the model is therefore limited by approximately 0.7 MIITS (All simulations were carried out within this range.) However, any errors such as this induced by time step differences were global, i.e. trends in results did not change with the time step, and larger time steps gave more conservative data, as in the above case. All data for a given study was collected from QUABER using the same simulation time step.

Quench detection in an actual magnet will occur by measuring the voltage between the two apertures through a bridge circuit, and triggering magnet protection when a threshold, 0.2 V for example, is detected. In the QUABER models the total magnet voltage is measured to give the detection voltage. In the actual bridge circuit, there is a resistive voltage divider that reduces the detection voltage by a factor of two. Thus, to convert the detection voltages presented here into the actual voltages that must be detected by the circuit, one must divide by two. For example, a 0.2 V detection level actually corresponds to a 0.1 V output from the bridge that feeds into the detection circuitry.

#### 2.1.2. Turn-to-turn quench propogation time (*ttx*)

The results of the simulations presented in Figure 5 cover the entire range of pessimistic and optimistic values for the propagation time between adjacent turns of the MB dipole magnet. The value normally used is ttx = 30 ms between adjacent turns in the cable. If this value is changed by 25 ms, the value of quench load changes up to 1 MIITS. These simulations were carried out holding the switch delay and all heater firing times constant. In reality, a change in the turn-to-turn delay would also cause a change in detection time, not considered here.

### 2.1.3. Quench propogation velocity (quench\_velocity)

This parameter is the velocity of the quench down the length of the magnet, i.e. perpendicular to the cross section of Figure 1. Measured values of quench velocities at nominal current are about 1500 cm/s to 2000 cm/s [4]. This type of uncertainty has little effect on the model (see Figure 6). As above, these simulations were carried out holding the switch delay and heater firing times constant.



Turn-to-turn quench propogation vs. quench load

Figure 5

### 2.1.4. RRR

In both studies above, simulations were carried out with two different sets of RRR values. Although not presented in the graphs, there is a constant relationship between the two. If the



#### Quench velocity vs. quench load

Figure 6

outer RRR value is lowered from 180 to 130, the corresponding quench load decreases by 1.2 MIITS in both studies in a linear fashion. However, quench loads are not easily compared since the change in RRR also affects the hot spot temperature in the opposite way. In these cases, this decrease of 1.2 MIITS corresponds to a decrease in hot spot temperature of approximately 7 K. Usually, one might expect a lower RRR to increase the hot spot temperature. However, at low temperatures, a lower RRR means an increased resistivity (see Figure 2). This causes faster resistance development and current decay, resulting in these lower temperatures. A value of RRR = 180 is used exclusively in further studies. As above, these simulations were carried out holding the switch delay and heater firing times constant.

Since the inner layer is quenched late, and all turns are quenched at the same time in this model, the RRR of the inner layer has only a small effect on quench load. With both 0.1 V and 0.2 V detection, the rise in quench load caused by an increase in the inner layer RRR from 150 to 200 (with outer layer RRR held constant at 180) was only 0.09 MIITS in both cases. This difference is negligible, as it is beyond the general time step accuracy of the model.

### 2.1.5. Copper and heaters lengths (*len\_cu* and *len\_heat*)

The interaction between lengths of copper plated and heated parts of the heater cycles was studied holding other values constant. As expected, the lowest quench load occurred with the greatest heated length. Using the greatest length, of course, is not feasible because the energy

needed to fire such a heater is too large, but this shows that small changes in the heater design should not have large influences on resulting quench loads.



### Quench load dependence on heater design

Figure 7

### 2.1.6. Quench origin

The most likely place for a quench is in the high-field region of a magnet, since the presence of a stronger magnetic field lowers the critical temperature for superconductivity. This study compares detection times at various voltages for a quench starting (see Figure 1) in a high field region (quench origin 1), and a low field region (quench origin 2). For detection at 0.1V, 6.5 additional milliseconds were required to detect the quench at quench origin 2 with respect to quench origin 1. Detecting at a threshold of 0.2 V, 11.3 additional milliseconds were needed for detection. Table 3 summarises these results for outer layer RRR = 180 and 150 (in parentheses).

Detection voltage [V]	Detection time, quench origin 1 RRR=180 (RRR=150) [ms]	Detection time, quench origin 2 RRR=180 (RRR=150) [ms]
0.1	19.1 (12.4)	25.6 (19.2)
0.2	26.1 (18.7)	37.3 (31.0)
0.3	31.1 (24.6)	46.0 (38.9)
0.5	41.4 (34.9)	58.4 (49.7)

Table 3: Quench origin effects

The expected differences will have two main causes:

- Resistance development takes place more slowly in the low field region, resulting in later detection times
- The quench velocity is lower, and although not taken into account above, will serve only to enhance these differences in detection times

### 2.2. Magnet current effects

In order to study how different current levels affect the protection, the times required to reach different detection voltage levels must be found. To determine the appropriate switch delay (*swdel* in Table 1) to use in the computer model, simulations were run with no heater firings, and the time was noted at which the desired voltage level (whole-magnet voltage) was reached. The table below summarises the results. A 5 ms validation period was added to the detection time to obtain the final values for the switch delays. This shows, in essence, the time it takes to detect a quench at various current levels and for different detection times.

current [kA]	t(.1V) [ms]	t(.2V) [ms]	t(.3V) [ms]	t(.5V) [ms]
0.800	824.5	1442.4	2060.2	3268.8
1.500	332.1	497.8	656.5	968.0
3.000	128.3	179.2	233.2	304.3
4.500	77.6	109.9	124.2	167.1
6.000	57.6	73.2	80.9	111.2
9.000	26.7	35.9	47.3	59.4
11.796	19.1	26.1	31.1	41.4

#### Table 4: Current effects

Heater delays were then calculated by adding certain offsets to the switch delays. The high and low heater delays used for these tests were calculated using the following formulae [2], producing expected values:

$$ht \quad delay \quad high = 270e^{-0.185I[k4]}[ms]$$
(2)

$$ht \_delay \_low = 270e^{-0.14I[kA]}[ms]$$
 (3)

The quench velocity, turn-to-turn propagation time and peak magnetic field were scaled appropriately to each current level in all tests.

To determine which detection threshold will be appropriate, quench loads and hot spot temperatures obtained through quenches at various currents and detection threshold levels were compared. (See Figure 8.) +

Between the levels of 0.1 V and 0.5 V, there is a significant 99.71 K difference in hot spot temperature and 3.072 MIITS at nominal current. With an adiabatically-calculated hot spot temperature of 477.09 K at 0.5 V detection, 0.5 V would be an unacceptable detection level. Under adiabatic conditions, a 0.2 V detection level appears to produce a rather high temperature as well (406.5 K), but suggests that this would be an acceptable detection threshold for the magnet protection system under appropriate cooling conditions. Note that this corresponds to an output to the detection circuit of 0.1 V because of a voltage divider in the detection bridge.



#### Quench load dependence on current

The detection level plays an unimportant role in the resistance development, which is governed almost entirely by the current, as can be seen in the following equation used for its calculation:

$$resdev = \frac{v_magnet - L\frac{di}{dt}}{i}$$
(4)

where *resdev* is the resistance development,  $v_magnet$  is the voltage across the magnet, L is the magnet's inductance, and i is the current flowing through the magnet (see Figure 9). A second order polynomial curve fit was applied to the simulation results. The results show that the QUABER model is operating properly, as the energy dissipated into the magnet after a quench goes quadratically with the current.



### Current vs. resistance developed

Figure 9

# 2.3. Failure modes

### 2.3.1. Heater failures

A quench at full current (11.796 kA) that is detected at a threshold of 0.2V detection and a validation period of 5ms would cause a quench load of 62.5 MIITS and a corresponding adiabatically-calculated hot spot temperature of 2061 K, if heaters failed (considering no quench in aperture 2 and inner layers, natural quench starts in aperture 1). A magnet under these conditions would be seriously damaged. However, this situation is unrealistic. In reality, the quench would spread throughout the entire magnet and quench-back would occur.

*Quench-back* is an effect caused when the rest of the magnet, i.e., the parts not near the quench origin, quench due to eddy currents. The eddy currents are generated due to a strong dB/dt during a current decay after a quench. The eddy currents go via contact resistances between strands of the superconducting cable, causing heat to be generated. If the temperature exceed the critical temperature, the quench-back starts. A recent quench of a 15-m long dipole magnet (MBP2N1v2) produced, when heaters were unable to fire, a quench load of 43 MIITS [5]. To duplicate this effect in a simulation, three regions of a magnet were artificially quenched at a certain time in a computer model. The following times resulted in obtaining an identical quench load of 43 MIITS:

Magnet region	Simulated quench time
High field region, outer layer	145 ms
Low field region, outer layer	175 ms
Inner layer	240 ms

This gives some indication as to the importance of including quench-back effects into a simulation model, as is done in the heater study. It is not accounted for in this failure study because quench-back at low currents is unlikely.

Simulations were carried out to determine the point at which the magnet is endangered, not assuming quench-back. At lower currents (under 3 kA), the quench load remains under 38.8 MIITS regardless of detection threshold. If a quench were to occur during injection, even with a heater failure, the magnet would be safe. Notable here is the fact that the protection diode still turns on, even if heaters fail at 0.8 kA. The quench detection, as can be seen in Figure 10, plays only a small role in this study. The differences at lower currents are caused by longer differences between detection times, which converge at high currents.



### Heater failure effects on quench load

Figure 10

If the nominal current were under 2-3 kA (possibly higher with quench-back effects), heater strips would be unnecessary, since the magnet is inherently safe at those currents.

Heater position plays an important role in quench protection. Presented below are situations at nominal current, 0.2 V detection with 5 ms validation period (quench-back effects included as indicated). The offsets given are time from detection at which heaters become effective. If

low field heaters fail or are not fired, the high field heaters alone are able to protect the magnet adequately in this model. However, low field heaters alone cannot protect the magnet with the assumed parameters if high field heaters fail. New experimental results showed that LF heaters alone might be able to be sufficient due to change heater parameters that reduces the heater delays. The inner layer quench has less effect.

High field heater offset [ms]	Low field heater offset [ms]	Inner layer quench time [ms]	Quench load [kA*kA*s]
30.4	51.8	101.8	35.67
30.4	51.8	no quench	36.63
30.4	no firing	101.8	36.87
30.4	no firing	no quench	40.61
No firing	51.8	101.8	43.93
No firing	51.8	no quench	46.95

Table 6: Efficacy of low and high field heaters

### 2.3.2. Protection diode failures

Although extremely unlikely, a protection diode failure in which current is blocked, i.e. the diode failure creates an open circuit instead of a short, would seriously damage a magnet at high current. Studies were not carried out for currents above 3 kA, since a quench at this current causes quench loads of 54.5 MIITS at 0.1 V detection and 65.1 MIITS at 0.5 V detection, and corresponding adiabatic hot spot temperatures of 960.5 K and 1080.6 K, respectively, which would be too problematic for the magnet. If a quench were detected immediately upon injection, however, regardless of the detection threshold used, the magnet would still be protected even with this type of failure (see Figure 11).



Diode failure at low currents (heaters are fired)

Figure 11

# 3. Heater study

To show the effect of heaters in the MB dipole, voltages from the simulation of a quench of a single magnet in which all heaters were fired at the same time (250 ms) are shown below. The quench was also forced to start in the inner layer at the same time to simulate the quench back effect. The other parameter settings are the extraction resistor  $rex = 27 \text{ m}\Omega$ , turn-to-turn delay ttx = 30.5 ms, and the initial current of 11.0 kA in this case. This test was motivated by the massive quench-back that occurred in test MBP2N1v2 when heaters were unable to be fired.

In Figure 12, at 50 ms, as a result of the detection of a quench, the voltage source is switched off and the extraction resistor immediately becomes the most resistive part of the circuit. For that reason all magnet voltages drop. Because the quench originates in aperture 1, upper pole, outer layer, the resistance from that element (orig.ou1, in this case) grows rapidly and causes a voltage rise. Without quench back, this voltage would continue to rise to just above 1500 V. In this case, however, the simulated quench back causes a sharp increase in resistance in the other parts of the magnet, causing the inductive voltage of the quench origin signal to dominate temporary. As can be seen, the inner layer voltages rise while the others fall. This is because the inner layers are all quenched at the same time, so when the inner layers quench their instantaneous resistance development is much larger in the simulation than those of the outer layers.



At 263 ms, the resistance voltage dominates again in the quench origin signal. This causes the voltage turn-around after which the quench propagation continues naturally.

The firing of the heaters causes an ultimate lowering in internal magnet voltages. This, in turn, affects the current decay and the quench load in a positive way. One aim of the heater simulations that follow (see Section 3.1) is to determine to what extent heater delays will be acceptable for the protection system to still function.

### 3.1. Comparison single magnet/magnet in series

The family size for the main dipole magnets is 154 magnets. These simulations compare induced quench load for a variety of detection voltages and delays. They were carried out using a 1500 cm/s quench velocity. Also, the switch delays/heater delays were held constant, not the detection voltages, so those indicated in Table 5 represent only approximate detection voltages. The average difference in quench load among the eight tests was 0.68 MIITS, and, as in Figure 11, this is similar for all tests. These tests represent the extreme values used in the main heater study, performed only on magnets in series. The results for a single magnet can be estimated by subtracting 0.68 MIITS from the quench load of an equivalent series magnet. The reason for this difference is that the fast current decay in a single magnet starts immediately when the heaters become effective, whereas in a series of magnets the turn on voltage of the diode has to be reached before the current starts to decay fast. Fast current decay means a time decay constant  $\tau$  of 200 - 300 ms, whereas the decay time constant for the whole series of 154 magnets is about 100 s.

Indicator	Detection	Validation	Switch	High field	Inner layer
	[V]	time [ms]	delay [ms]	heater	quench
				delay [ms]	time [ms]
1	0.1	5	24.1	54.1	134.1
2	0.1	10	29.1	59.1	139.1
3	0.2	5	31.1	61.1	141.1
4	0.1	5	24.1	59.1	189.1
5	0.1	10	29.1	64.1	194.1
6	0.2	5	31.1	66.1	196.1
7	0.5	5	46.4	76.4	156.4
8	0.5	5	46.4	81.4	211.4

Table 7: Description of single/series magnet tests



### Quench load for various tests

Figure 13

# **3.2.** Series magnet heater studies

### 3.2.1. All heater delays varied proportionally

These studies were carried out using a quench velocity of 2000 cm/s and 0.1 V detection with a 5 ms validation period. With the switch delay held constant, the HF heater delay, i.e., time from start of quench when the high field heater becomes effective (including detection) was examined first. It was varied between 40 ms and 110 ms while the LF heater delays and inner layer quench times were adjusted linearly, with the LF heaters always firing 15 ms after the HF heaters, and the inner layers quenching 100 ms later. This study was performed for two RRR sets (see Figure 12), although they should not be compared with each other, as the quench load refers to a different temperature for the two RRR sets (see Figure 2). This shows,

in effect, the overall efficacy of the heaters. The quench load is approximately 20 - 30 MIITS lower than in the case where the heaters fail.

The HF heaters were then held constant at 53.5 ms while LF heaters and inner layer quench time were adjusted linearly as above. The LF heaters are not as effective as the HF heaters because they cover fewer magnet turns and exist in a low-field region (see Figure 15).

Finally, the HF and LF heater delays were held constant at 53.5 and 68.5 ms, respectively, while the inner layer quench was studied. Although not shown in Figure 14, as the inner layer quench time approaches infinity, the quench load approaches 35.4 MIITS. Compared to the effect of the heaters, the quench of the inner layer is negligible.



### Quench load dependence on low field heater delay (high = 53.5 ms, inner adjusted accordingly)

Figure 14





Figure 15





Figure 16

### 3.2.2. All heater delays changed independently

As can be seen in Figure 15, the inner layer quench has the least effect on quench load, and the firing of the high heater delay. A 0.2 V detection threshold was chosen for the majority of the studies because it has the greatest possibility of being implemented. Additionally, some tests were conducted at 0.1 V, as can be seen in Section 3.1, and at 0.5 V (see Appendix B). These studies were carried out with a quench velocity of 1500 cm/s. Results presented below use the offset, that is, time after detection and validation at which heaters become effective.



### .2 V detection heater study



# **3.3.** Aperture quenching asymmetries (scattering)

Four series of simulations were run to determine the effects of differences between aperture firing times. In all simulations, the quench originates in aperture 1. First high field heater asymmetries were examined. The firing time differences in Figure 18 indicate which aperture fired late and by what amount of time. Small firing differences have only small effects (quench time of inner layer held constant).

Similar simulations were carried out to study low field heater asymmetries. Here (see Figure 19), the results show situations in which a heater fires early by a certain amount of time or fails. Failure of a half of the LF heaters is not serious.



### High field heater asymmetries

Figure 18

# Low field heater asymmetries



Figure 19

### Inner layer asymmetries



Figure 20

In the case of scattering of the inner layer quench time, it is apparent that this effect is very small compared to the effects of the heaters (see Figure 20), as the inner layer quenches much later.

The effects of an asymmetrical heater firing can be seen clearly in intra-magnet voltages. Figures 21 - 23 show effects of increasing scattering within the magnet. The most prominent effect is the increasing voltage in the part of the magnet containing the quench origin (outer layer, upper pole, aperture 1 as in Figure 1). Upper plots show aperture 2 voltages; aperture 1 voltages are below. The graphs were generated by SABER for each aperture, pole and layer in the magnet. For simplicity, all heat elements fire (and inner layer quench occurs) at the same time, viz. 110 ms, or late as indicated in the figures.

In Figures 22 and 23, note the increasing voltages in aperture 1. As the quench starts later in aperture 2, the inductive voltages dominate causing the voltages to decrease. Consequently the resistance development is taking place more in aperture 1, and, in the extreme case where no quench is allowed to propagate to aperture 2 (Figure 23), the outer layer voltages in aperture 1 rise to nearly 1000 V. In Figures 22 and 23, the voltages of the inner layers are predominately inductive and have negative voltages at some points because they do not have as much resistance development as the outer layers.



Figure 21: All heaters firing together (normal situation)



Figure 22: Aperture 2 quenches 10 ms late

The final asymmetry study assesses the situation where three components fail in a magnet. In Figure 24, A = aperture, LF = low field heater failure, HF = high field heater failure, and IN = no quench in inner layer. Thus, in A2 failure, for example, the aperture never quenches (since in QUABER the quenching of the aperture opposite the quench origin must be initiated by a "heat" element). These values were generated using 0.2 V detection with a 5 ms validation period.



Figure 23: No quench in aperture 2 (no heaters fired, no inner layer quench)



#### Massive asymmetries

Figure 24

# 3.4. Remarks

A detection level of 0.2 V is acceptable, which corresponds to a 0.1 V detection threshold entering the detection circuitry from the bridge. In all cases, the protection diode turned on, even at an injection current level of 0.8 kA without heaters being effective. Heaters are not

necessary for protection until approximately 2 kA. High field heaters are much more effective than low field heaters at protecting a quenching magnet. High field heaters alone should offer sufficient protection. Small differences between heater delays in different apertures do not cause dangerous intra-magnet voltages.

# 4. Acknowledgements

Thanks to R. Schmidt for his support and proofreading and to F. Rodriguez Mateos for many suggestions, as well as the rest of ICP for their help. Thanks to S. Russenschuck for providing the required design parameters. Thanks to all of MTA for their measurements that allow calibrating the simulation model.

# 5. References

- 1. F. Rodriguez et al., QUABER 4.0 User Guide.
- 2. F. Sonnemann et al., Quench process and protection of LHC dipole magnets, LHC Project Note 184
- 3. F. Rodriguez et al., The protection system for the superconducting elements of the LHC of CERN, LHC Project Report 283
- 4. R. Schmidt., Private communication.
- 5. A. Siemko., Private communication.

# **APPENDIX A: DATA FOR MAGNET CURRENT EFFECTS**

CONNENTION	UDY ON MB	DIPOLE	MAGNET										
ourropt [kA]	tor detection	onno I	heaters firing	t( 2)/) [mc]		t/ 5\/) [mc]		heater delay offse	ets	auonch volocity [m/c	tty [mc]	poakfield	filonamo
Current [KA]	t (.1v) [ms]	924 5	(.2V) [ms]	t(.3v) [ms]	2060.2	t(.5V) [ms]	2260 0	nign [ms]	10w [ms]	quench velocity [m/s	ttx [ms]	peakrieid	mbourront001 pin
0.0	5	332.1	/07.9		656.5		967.98	204.6	241.4	24	50 50.0 54 50.2	1.00	mbcurrent002 sin
3	5	128.3	179 2		233.2		304.31	155.0	177.4	5.	9 42.2	2 19	mbcurrent002.sin
4.5	5	77.6	109.9		124.2		167.14	117.4	143.8	7.6	3 38.2	3.28	mbcurrent0045.sin
6	5	57.6	73.2		80.9		111.16	89.0	116.6	10.	7 35.5	4.38	mbcurrent004.sin
9	)	26.7	35.9	1	47.3		59.362	51.1	76.6	15.3	26 32.1	6.57	mbcurrent005.sin
11.796	6	19.1	26.1		31.1		41.396	30.5	51.8	20.0	0 30.0	8.61	mbcurrent006.sin
11.796 single		14.699	23.216		30		41.018						
11	just for the fi	nal hhh s	simulations							18.0	30.5	8.03	
11.796origmov	,	25.578	37.378	1	45.965		58.368						mborig.sin
11.796RRRIow	v	12.4	18.71		24.64		34.9						
RRRIoworigmo	v	19.2	30.99		38.9		49.66						
using 5ms swd	el offset from	time of c	letection for validati	on, heater del	ays belo	ow calculated u	ising the	offsets above					
GROUP 1: det	tection at .1V								RESULTS				
current [kA]	swdel [ms]		high heaters [ms]	low heaters	s [ms]	inner heater	s [ms]	filename	milts [kA*kA*s]	hot spot [K]	resistive dev [Ohm]	max Vmag [V]	time of max V [s]
0.8	5	829.5	1062.4		1070.9	do not fire		mbcurrent101.sin	2.2/1/	22.60	0.023	8.3	1.1967
1.5		337.1	541.7		556.0	do not fire		mbcurrent102.sin	6.046	32.8	0.029	8.3	0.6053
3	5	133.3	288.3		310.7	do not fire	200.4	mbcurrent103.sin	14.654	56.4	3 0.073	8.3	0.3114
0		21.7	151.5		1/9.1		299.1	mbourront105 oin	24.79	125.	0.292	0.3	0.1567
11 706	,	24.1	54.6		75.0		125.0	mbourront106 sin	25.062	233.	0.073	0.3	0.0650
11.750	,	24.1	54.0	,	75.5		120.9	mbcurrent100.3m	33.903	311.	1.174	0.5	0.0307
GROUP 2: det	tection at 2V												
current [kA]	swdel [ms]		high heaters [ms]	low heaters	s [ms]	inner heater	s [ms]	filename					
0.8	s in der [e]	1447 4	1680.3	ion noutore	1688.8	do not fire	0 [0]	mbcurrent201 sin	2 6559	23.6	4 0.023	83	1 8145
1.5		502.8	707.4		721 7	do not fire		mbcurrent202 sin	6 422	33.6	8 0.020	8.3	0 7707
		184.2	339.2		361.6	do not fire		mbcurrent203.sin	15.117	57.7	0.07277	8.3	0.3624
6		78.2	167.2		194.8		314.8	mbcurrent204 sin	25 356	131 (	0 29181	83	0 1724
9		40.9	91.9		117.4		197.4	mbcurrent205.sin	32,175	252.0	0.71131	8.3	0.0947
11.796	5	31.1	61.5		82.9		132.9	mbcurrent206.sin	36.924	406.0	1.1726	8.3	0.0636
GROUP 3: det	tection at .5V												
current [kA]	swdel [ms]		high heaters [ms]	low heaters	s [ms]	inner heater	s [ms]	filename					
0.8	3	3273.8	3506.7		3515.2	do not fire		mbcurrent501.sin	3.767	26.5	64 0.02245	8.3	3.6405
1.5	5	973.0	1177.6		1191.8	do not fire		mbcurrent502.sin	7.469	35.8	0.02908	8.3	1.2399
3	3	309.3	464.3		486.7	do not fire		mbcurrent503.sin	16.192	61.65	9 0.07272	8.3	0.4874
6	5	116.2	205.1		232.7		352.7	mbcurrent504.sin	26.719	144.	3 0.29164	8.3	0.21001
9	)	64.4	115.4		140.9		220.9	mbcurrent505.sin	34.064	291.3	0.71105	8.3	0.1181
11.796		46 4											
	,	40.4	76.8		98.2		148.2	mbcurrent506.sin	39.035	477.0	9 1.1716	8.3	0.07871
	,	40.4	76.8		98.2		148.2	mbcurrent506.sin	39.035	477.0	1.1716	8.3	0.07871
FAILURE 1: he	, eater failure a	40.4 t .8 kA (i	76.8 nner heaters not fire	ed in any of th	98.2 ese tria	ls)	148.2	mbcurrent506.sin	39.035 RESULTS	477.0	1.1716	8.3	0.07871
FAILURE 1: he	eater failure a swdel [ms]	40.4 t .8 kA (i	76.8 nner heaters not fir high heaters [ms]	ed in any of th low heaters	98.2 iese tria <b>s [ms]</b>	l <u>s)</u> inner heater	148.2 s [ms]	mbcurrent506.sin filename	39.035 RESULTS miits [kA*kA*s]	477.0	resistive dev [Ohm]	8.3 max Vmag [V]	0.07871 time of max V [s]
FAILURE 1: he detection V 0.1	eater failure a swdel [ms]	46.4 <u>t .8 kA (i</u> 829.5	76.8 nner heaters not fir high heaters [ms] 1062.4	ed in any of th low heaters failure	98.2 lese tria <b>s [ms]</b>	ls) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin	39.035 RESULTS miits [kA*kA*s] 3.0325	477.0 hot spot [K] 24.64	vesistive dev [Ohm] 16 0.0145	8.3 max Vmag [V] 8.3	0.07871 time of max V [s] 1.3593
FAILURE 1: he detection V 0.1 0.1	eater failure a swdel [ms]	46.4 t .8 kA (i 829.5 829.5	76.8 nner heaters not fir high heaters [ms] 1062.4 failure	ed in any of th low heaters failure	98.2 l <u>ese tria</u> <b>5 [ms]</b> 1070.9	inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin mbfailure1b.sin	39.035 RESULTS miits [kA*kA*s] 3.0325 3.0702	477.0 hot spot [K] 24.6- 24.7-	1.1716 resistive dev [Ohm] 16 0.0145 18 0.0156	8.3 max Vmag [V] 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473
FAILURE 1: he detection V 0.1 0.1 0.1	eater failure a swdel [ms]	46.4 t .8 kA (i 829.5 829.5 829.5	76.8 nner heaters not fir high heaters [ms] 1062.4 failure failure	ed in any of th low heaters failure failure	98.2 ese tria <b>5 [ms]</b> 1070.9	l <u>s)</u> inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin mbfailure1b.sin mbfailure1c.sin	39.035 RESULTS miits [kA*kA*s] 3.0325 3.0702 29.567	477.0 hot spot [K] 24.6 24.7 120	resistive dev [Ohm]           6         0.0145           18         0.0156           .9         0.0382	8.3 max Vmag [V] 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 100.8
FAILURE 1: he detection V 0.1 0.1 0.1 0.2	eater failure a swdel [ms]	46.4 <u>t .8 kA (i</u> 829.5 829.5 829.5 1447.4	76.8 nner heaters not firm high heaters [ms] 1062.4 failure failure 1680.3	ed in any of th Iow heaters failure failure	98.2 ese tria <b>5 [ms]</b> 1070.9	ls) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin mbfailure1b.sin mbfailure1c.sin mbfailure2a.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5945	477.0 hot spot [K] 24.6 24.7 120 26.1	resistive dev [Ohm] 66 0.0145 18 0.0156 9 0.0382 16 0.014557	8.3 max Vmag [V] 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 100.8 1.9772
FAILURE 1: he detection V 0.1 0.1 0.2 0.2	eater failure a swdel [ms]	46.4 t .8 kA (i 829.5 829.5 829.5 1447.4 1447.4	76.8 nner heaters not firm high heaters [ms] 1062.4 failure failure failure	ed in any of th Iow heaters failure failure failure	98.2 ese tria [ms] 1070.9 1688.8	ls) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1b.sin mbfailure 1c.sin mbfailure 2a.sin mbfailure 2b.sin	39.035 RESULTS milts [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5945	477.0 hot spot [K] 24.6 24.7 120 26.1 26.0 26.0	resistive dev [Ohm] 6 0.0145 8 0.0156 9 0.0382 6 0.014557 1 0.015811 4 0.015811	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 100.8 1.9772 2.0665
FAILURE 1: he detection V 0.1 0.1 0.2 0.2 0.2	swdel [ms]	46.4 t .8 kA (i 829.5 829.5 829.5 1447.4 1447.4 1447.4	76.8 nner heaters not fir high heaters [ms] 1062.4 failure failure failure ailure	ed in any of th Iow heaters failure failure failure failure	98.2 <u>ese tria</u> 5 [ms] 1070.9 1688.8	ls) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin mbfailure1b.sin mbfailure2a.sin mbfailure2a.sin mbfailure2a.sin mbfailure2b.sin	39.035 RESULTS miits [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5945 3.5956 29.117 4.7422	477.0 hot spot [K] 24.6 24.7 120 26.1 26.0 117. 26.0	ig         1.1716           resistive dev [Ohm]         6         0.0145           8         0.0145         0.01362           9         0.0382         0.014557           10         0.015811         1         0.03647           11         0.03647         0.044577         0.0444457	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 100.8 1.9772 2.0665 91.443 2.902
FAILURE 1: he detection V 0.1 0.1 0.1 0.2 0.2 0.2 0.5	swdel [ms]	40.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8	76.8 nner heaters not fir high heaters [ms] 1062.4 failure failure failure failure failure 3506.7	ed in any of th Iow heaters failure failure failure failure failure failure	98.2 ese tria s [ms] 1070.9 1688.8	Is) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin mbfailure1b.sin mbfailure2a.sin mbfailure2c.sin mbfailure2c.sin mbfailure2c.sin	39.035 RESULTS milts [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163	477.0 hot spot [K] 24.6 24.7 120 26.1 26.0 117. 28. 29.7 20.7	resistive dev [Ohm] 66 0.0145 18 0.0156 19 0.0322 16 0.014557 11 0.015811 1 0.03647 77 0.01448	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1008 1.9772 2.0665 91.443 3.803 2.065
FAILURE 1: he detection V 0.1 0.1 0.2 0.2 0.2 0.2 0.5 0.5	eater failure a swdel [ms]	40.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8	76.8 nner heaters not fir high heaters [ms] 1062.4 failure failure failure 3506.7 failure	ed in any of th low heaters failure failure failure failure failure	98.2 eese tria s [ms] 1070.9 1688.8 3515.2	(s) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin mbfailure1c.sin mbfailure2c.sin mbfailure2c.sin mbfailure5a.sin mbfailure5a.sin	39.035 RESULTS miits [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5945 3.5945 2.9.117 4.7163 4.6675 20.455	477.4 hot spot [K] 24.6- 24.7- 120 26.1: 26.0: 117. 28.7 28.7 28.7 28.7 28.7 28.7 28.7 28	resistive dev [Ohm] fe 0.0145 16 0.0145 18 0.0156 19 0.0382 16 0.01455 11 0.03847 11 0.03647 17 0.01448 11 0.01606 2 0.01606	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 100.8 1.9772 2.0665 91.443 3.8859 3.8859
FAILURE 1: he detection V 0.1 0.1 0.2 0.2 0.2 0.5 0.5 0.5 0.5	eater failure a swdel [ms]	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8	76.8 nner heaters not fir high heaters [ms] 1062.4 failure failure failure failure failure failure failure	ed in any of th Iow heaters failure failure failure failure failure failure failure	98.2 eese tria s [ms] 1070.9 1688.8 3515.2	is) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure1a.sin mbfailure1b.sin mbfailure2a.sin mbfailure2a.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin	39.035 RESULTS milts [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163 4.6675 28.485 28.495	477.4 hot spot [K] 24.6 24.7 120 26.1 126.0 117. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 29.7 29.7 20.7 20.7 20.7 20.7 20.7 20.7 20.7 20	Image: resistive dev         Ohm]           resistive dev         Ohm]           66         0.0145           88         0.0158           99         0.0382           16         0.01455           11         0.03847           77         0.0145811           10         0.03642           21         0.00405	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 100.8 1.972 2.0665 91.443 3.803 3.8859 79.207 27.645
FAILURE 1: ht detection V 0.1 0.1 0.1 0.2 0.2 0.2 0.5 0.5 0.5 0.5 0.5 0.5	eater failure a swdel [ms]	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8	76.8 nner heaters not fir high heaters [ms] failure failure failure failure failure failure failure	ed in any of th Iow heaters failure failure failure failure failure failure failure failure failure	98.2 ese tria [ms] 1070.9 1688.8 3515.2	is) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1a.sin mbfailure 2a.sin mbfailure 2a.sin mbfailure 2a.sin mbfailure 5a.sin mbfailure 5b.sin mbfailure 5c.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5956 29.117 4.7163 4.6675 28.485 26.427	477.4 hot spot [K] 24.6. 24.7. 120 26.1: 26.0. 117. 28.7 28.7 28.7 28.7 28.7 28.7 28.7 28	Initial         Initial           resistive dev         Ohm]           66         0.0148           89         0.0382           66         0.0145811           1         0.036811           1         0.036811           1         0.036811           1         0.036811           1         0.036811           1         0.014641           1         0.014642           10         0.03432           12         0.028495	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645
FAILURE 1: ht detection V 0.1 0.1 0.2 0.2 0.2 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5	eater failure a swdel [ms]	40.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8 3273.8	76.8 nner heaters not fir high heaters (ms) 1062.4 iailure iailure iailure 3506.7 iailure iailure iailure iailure	ed in any of th low heaters failure failure failure failure failure failure failure failure	98.2 ese tria [ms] 1070.9 1688.8 3515.2 these tri	Is) inner heater do not fire	148.2 s [ms]	mbcurrent506.sin filename mbfailure 1b.sin mbfailure 1b.sin mbfailure2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin	39.035 RESULTS mits [kA'kA's] 3.0325 3.0702 29.567 3.5945 3.5945 3.5956 29.117 4.7163 4.6675 28.485 28.485 26.427 RESUILTS	477.4 hot spot [K] 24.6 24.7 120 26.1 26.0 26.0 26.0 26.0 26.0 27.2 28.7 117. 28.7 112. 97.4	ig         1.1716           resistive dev [Ohm]         0.0145           i6         0.0145           i8         0.0158           i9         0.0382           i6         0.01451           i1         0.036811           i2         0.0343           i2         0.03449	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [5] 1.3593 1.473 100.8 1.9772 2.0665 91.443 3.803 3.803 3.803 79.207 37.645
FAILURE 1: ht detection V 0.1 0.1 0.2 0.2 0.2 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5	eater failure a swdel [ms]	48.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8 3273.8	76.6 nner heaters not fir high heaters [not fir high heaters [not alilure 1680.3 failure 3506.7 failure	ed in any of th low heaters failure failure failure failure failure failure failure failure failure failure failure failure	98.2 ese tria s [ms] 1070.9 1688.8 3515.2 these tria	IS) inner heater do not fire als) inner heater	148.2 s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1b.sin mbfailure 2a.sin mbfailure2a.sin mbfailure2a.sin mbfailure5a.sin mbfailure5a.sin mbfailure6a.sin filename	39.035 RESULTS milts (KA*Ka*s) 3.0325 3.0325 3.5945 3.5945 3.5945 3.5945 2.9117 4.7163 4.6675 28.485 26.427 RESULTS milts (KA*Ka*s)	477.4 hot spot [K] 24.6- 24.7 26.0: 26.0: 117. 28.7 28.7 112: 97.40 hot spot [K]	Image: system         Image: system           resistive dev [Ohm]         0.0145           iii         0.0156           iii         0.0158           iii         0.01457           iii         0.014511           1         0.015811           1         0.014457           10         0.01442           11         0.01442           12         0.028495           resistive dev [Ohm]         resistive dev [Ohm]	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1008 1.473 2.0665 91.443 3.803 3.883 79.207 37.645 time of max V [s]
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5	eater failure a swdel [ms]	46.4 829.5 829.5 829.5 829.5 1447.4 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8	76.6 nner heaters not fin high heaters [ms] lailure 1680.2 lailure lailure lailure lailure lailure lailure lailure lailure lailure	ad in any of th Iow heaters failure failure failure failure failure failure failure failure failure failure failure failure failure	98.2 ese tria s [ms] 1070.9 1688.8 3515.2 these tri s [ms]	IS) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1b.sin mbfailure2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure6c.sin filename mbfailure102 sin	39.035 RESULTS mitts [kA'kA's] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mitts [kA'kA's] 28.14	477.4 hot spot [K] 24.6. 24.7 120 26.1: 28.0 117. 28.7 112: 28.7 112: 97.4 hot spot [K]	11.776           resistive dev [Ohm]           16         0.0148           18         0.0158           19         0.0382           16         0.0148           11         0.03681           12         0.01484           13         0.01484           14         0.01484           15         0.01484           16         0.01484           17         0.02449           resistive dev [Ohm]         0.0376	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 100.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 10.708
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.1           0.2	eater failure a swdel [ms]	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 t1.5 kA 337.1 502.8	76.8 nner heaters (ms) high heaters (ms) failure aliure failure	ad in any of the Iow heaters failure failure failure failure failure failure failure failure failure failure failure failure	98.2 ese tria 5 [ms] 1070.9 1688.8 3515.2 these tri 5 [ms]	is) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1b.sin mbfailure 1b.sin mbfailure 2b.sin mbfailure2b.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure6a.sin filename mbfailure102.sin	39.035 RESULTS mits [kA*k4*s] 3.0325 3.0325 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*k4*s] 28.14 28.84	477.4 hot spot [K] 24.6. 24.7. 26.0 117. 28.7 28.7 112. 37.4 hot spot [K] 123. 123.	11.1716           resistive dev [Ohm]           16         0.0148           18         0.0156           9         0.0328           16         0.014857           17         0.01541           1         0.03647           11         0.016441           12         0.03432           12         0.028495           resistive dev [Ohm]         17           17         0.0372	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1.473 1.072 2.0655 91.443 3.803 3.8839 79.207 37.645 time of max V [s] 10.679
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.6           0.7           0.1           0.2           0.5           0.7	swdel [ms]	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 1447.4 3273.8 327	76.6 nner heaters not fin high heaters [ms] lailure 1680.3 lailure 1680.3 lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure	ad in any of th <b>Iow heaters</b> failure failure failure failure failure failure failure failure failure failure failure failure failure	98.2 ese tria 5 [ms] 1070.9 1688.8 3515.2 these tria 5 [ms]	IS) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin	39.035 RESULTS mits [kA*ka*s] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*ka*s] 28.14 28.94 28.973	477.4 hot spot [K] 24.6. 24.7 120 26.1: 26.0 117. 28. 28.7 112: 97.4 hot spot [K] 123. 123. 123.	11.776           resistive dev [Ohm]           16         0.0148           9         0.0382           16         0.0146           11         0.0382           12         0.01481           13         0.01481           14         0.01481           15         0.028493           resistive dev [Ohm]         17           17         0.0377           19         0.0383           10         0.0384	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.5503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 10.708 10.679 10.563
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           0.5           0.5           0.5           0.5           0.5           0.6           0.5           0.6           0.1           0.2           0.5           0.6           0.7           0.6           0.7           0.6           0.6           0.6           0.6           0.6           0.6           0.6           0.7	swdel [ms] swdel [ms] infinite eater failure a swdel [ms]	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 373.8 375	76.8 nner heaters not fin high heaters [ms] 1062.4 iailure iailure 1680.3 iailure iailure iailure iailure iailure iailure iailure iailure iailure iailure iailure iailure iailure iailure	ad in any of th <b>Iow heaters</b> failure failure failure failure failure failure failure failure failure failure failure failure failure failure failure failure failure failure failure	98.2 ese tria [ms] 1070.9 1688.8 3515.2 these tri [ms]	(s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 15.sin mbfailure 2b.sin mbfailure2a.sin mbfailure3a.sin mbfailure5a.sin mbfailure6a.sin filename mbfailure202.sin mbfailure502.sin mbfailure502.sin	39.035 RESULTS mits [kA*ka*s] 3.0325 3.0325 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 28.14 28.93 29.412	477.4 hot spot [K] 24.6 24.7 120 26.1 26.0 127 28.7 117. 28.7 117. 28.7 112. 97.4 hot spot [K] 123.3 123.3 123.3 123.3 123.1 1	11.776           resistive dev (Ohm)           16         0.0145           18         0.0158           19         0.0382           16         0.01457           11         0.03817           12         0.0382           13         0.014511           14         0.015811           15         0.01448           10         0.028495           resistive dev (Ohm)           17         0.0372           18         0.0381           19         0.0382           105         0.0401	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 100.8 1.9772 2.0665 91.443 3.803 3.803 3.8859 79.207 37.65 time of max V [s] 10.708 10.708 10.708 10.619 10.553 9.148
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.2           0.2           0.5           0.6           0.7           0.8           0.1           0.2           0.2           0.5           no detection           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection	swdel [ms] swdel [ms] swdel [ms] swdel [ms] swdel [ms] swdel [ms]	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 327	76.8 nner heaters not filf high heaters [ms] high heaters [ms] hig	ed in any of th low heaters failure failure failure failure failure failure failure failure failure failure failure failure failure failure	98.2 ese tria [ms] 1070.9 1688.8 3515.2 these tri [ms]	(s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure2a.sin mbfailure2a.sin mbfailure5b.sin mbfailure5b.sin mbfailure5c.sin mbfailure6a.sin mbfailure62.sin mbfailure202.sin mbfailure602.sin	39.035 RESULTS mitts [kA*kA*s] 3.0325 3.0702 29.567 3.5946 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mitts [kA*kA*s] 28.14 28.93 28.14 28.93 29.412	477.4 hot spot [K] 24.6. 24.7. 120 26.1: 26.0. 117. 28. 28.7. 112. 97.40 hot spot [K] 123.4 123.4 123.4 123.4 123.4 123.4	11/17           resistive dev [Ohm]           66         0.0148           99         0.0382           66         0.01451           11         0.03681           12         0.01448           14         0.01448           15         0.01448           16         0.01448           17         0.0343           18         0.028495           19         0.0376           19         0.0387           15         0.0401	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 100.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 10.708 10.673 9.148
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.2           0.2           0.5           0.5           0.6           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.5           0.6           0.7	swdel [ms] infinite eater failure a swdel [ms] infinite	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 327	76.8 nner heaters not fir high heaters [ms] 1062.4 lailure 1680.2 lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure lailure	ad in any of th low heaters failure failure failure failure failure failure failure failure failure failure failure failure failure failure	98.2 ese trial [1070.9 1688.8 3515.2 these trial ese trial	(s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1a.sin mbfailure 2b.sin mbfailure2a.sin mbfailure2a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin mbfailure3a.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5946 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 28.973 29.412 RESULTS	477.4 hot spot [K] 24.6 24.7 120 26.1 26.0 117. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 112. 28.7 123. 123. 123. 123.	Image: system         Image: system           resistive dev         Ohm]           6         0.0145           8         0.0158           9         0.0382           66         0.01457           11         0.03681           12         0.03448           12         0.028495           resistive dev [Ohm]         0.0379           12         0.0381           15         0.0401	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.8859 79.207 37.645 time of max V [s] 10.708 1
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.2           0.5           no detection           FAILURE 2: hr           detection V           0.1           0.2           0.5           no detection           FAILURE 2: hr           0.1           0.2           0.5           no detection           FAILURE 3: hr           detection V	eater failure a swdel [ms]	46.4 t.8 kA (i 829.5 829.5 829.5 1447.4 1447.4 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8 1.447.4 1.447.4 1.447.4 3273.8 3273.	76.8 nner heaters not filf high heaters [ms] high heaters [ms] failure	ed in any of the low heaters failure	98.2 esse trial (ms) 1070.9 1688.8 3515.2 these trial (ms) (ms)	(s) Inner heater do not fire als) inner heater do not fire s) inner heater	148.2 s [ms] s [ms]	mbcurrent506.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure50.sin mbfailure50.sin mbfailure50.sin mbfailure50.sin mbfailure50.sin mbfailure50.sin mbfailure50.sin mbfailure50.sin mbfailure50.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5946 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 29.412 RESULTS mits kA*kA*s]	477.4 hot spot [K] 24.6. 24.7. 120 26.1. 123. 28.7. 112. 97.40 hot spot [K] 123. 123. 123. 123. 123. 123. 123. 123. 124. 123. 127	11/17/6           resistive dev [Ohm]           16         0.0145           18         0.0158           19         0.0148           11         0.0382           12         0.0144           11         0.0144           12         0.028495           resistive dev [Ohm]         0.0337           17         0.0337           19         0.0384           17         0.0375           19         0.0381           15         0.0401           resistive dev [Ohm]           15         0.0401	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1008 1.9772 2.0665 91.443 3.803 3.8839 79.207 37.645 time of max V [s] 10.708 10.679 10.553 9.148 time of max V [s]
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.5           0.5           0.5           0.5           0.5           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.1           0.1           0.1	eater failure a swdel [ms] infinite eater failure a swdel [ms] infinite eater failure a swdel [ms]	46.4 829.5 829.5 829.5 829.5 1447.4 1447	76.8 nner heaters not fir high heaters [ms] 1062.4 lailure 1680.2 lailure	ed in any of th Iow heaters failure	98.2 eese trial (ms) 1070.9 1688.8 3515.2 these tri (ms) ese trial	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1a.sin mbfailure 2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 28.973 29.412 RESULTS mits [kA*kA*s] 38.818	477.4 hot spot [K] 24.6: 24.7: 120 26.1: 26.0: 117: 28.7: 28.7: 112: 28.7: 112: 28.7: 112: 28.7: 112: 28.7: 112: 123: 123: 123: 123: 124: 125: 127: 125: 127: 127: 127: 127: 127: 127: 127: 127	11,1716           resistive dev (Ohm)           16         0.0148           18         0.0158           19         0.0382           16         0.0148           17         0.0148           11         0.01681           12         0.0348           12         0.02449           resistive dev (Ohm)         0.0378           19         0.0388           15         0.0401           15         0.0401           resistive dev (Ohm)         0.0401           15         0.0401           16         0.2054	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.8859 79.207 3.7645 time of max V [s] 10.708 10.619 10.553 9.148 time of max V [s] 2.799
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.2           0.5           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5	e atter failure a swdel [ms]	46.4 t.8 kA (i 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8 3273.8 3273.8 3273.8 t1.5 kA 337.1 502.8 973 t3 kA (ii 133.3	76.8 nner heaters not filf high heaters [ms] 1062.4 lailure	ed in any of th Iow heaters failure	98.2 ese tria s [ms] 1070.9 1688.8 3515.2 these tri s [ms] s [ms]	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire	148.2 s (ms) s (ms)	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1c.sin mbfailure 2c.sin mbfailure2c.sin mbfailure2c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure3c.sin mbfailure3c.sin	39.035 RESULTS miits [kA*ka*s] 3.0325 3.0702 29.567 3.5966 29.117 4.7163 4.6675 28.485 26.427 RESULTS miits [kA*ka*s] 28.973 29.412 RESULTS miits [kA*ka*s] 38.818 38.827	477.4 hot spot [K] 24.6. 24.7. 26.0. 117. 28.7 112. 97.40 hot spot [K] 123. 123. 123. 124. 28.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.9.7 29.	11.776           resistive dev [Ohm]           66         0.0145           18         0.0156           9.9         0.0136           11         0.015811           11         0.0154           12         0.0343           12         0.028495           17         0.0377           19         0.0384           17         0.0375           19         0.0381           15         0.0441           15         0.0401           12         0.0284           1         0.0371           1         0.0372           1         0.0374           10         0.0374           10         0.0374           10         0.0374           10         0.0374	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.473 1.072 2.0665 91.443 3.803 3.803 3.803 91.443 10.708 10.708 10.553 9.148 time of max V [s] 2.799 2.8 2.8 2.8 2.8 2.8 2.8 2.8 2.8
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5	eater failure a swdel [ms] swdel [ms] infinite eater failure a swdel [ms] swdel [ms]	40.4 t.8kA (i 829.5 829.5 829.5 1447.4 1447.4 3273.8 3273.8 3273.8 3273.8 3273.8 1447.4 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8 1247.4 1447.4 13273.8 1337.1 1502.8 973 1848.4 (ii 1333.3 1842.2 1348.4 144.2 1348.3 1842.2 1348.4 1442.4 1434.4 1434.4 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 1337.1 1348.4 1448.4 1434.4 1434.4 1434.4 1434.4 1434.4 1447.4 145.4 147.4	76.8 nner heaters not fin' high heaters [ms] high heaters [ms] lailure	ed in any of th Iow heaters failure	98.2 sese tria s [ms] 1070.9 1688.8 3515.2 these trial s [ms] s [ms]	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 1b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin mbfailure5c.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] RESULTS mits [kA*kA*s] 88.818 38.827 38.848	477.4 hot spot [K] 24.6. 24.7. 120 26.1: 26.0. 117. 28.3 287.7 112. 97.4 hot spot [K] 123.1 123.1 123.1 123.1 124.7 125.0 1	11.776           resistive dev (Ohm)           16         0.0148           9         0.0382           16         0.01481           1         0.0382           16         0.01481           1         0.0382           10         0.01481           11         0.0376           12         0.028495           resistive dev (Ohm)           17         0.0377           15         0.0401           resistive dev (Ohm)           12         0.2054           1         0.2056           1         0.2056           1         0.2056	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 10.708 10.679 10.708 10.679 2.799 2.89 2.799
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.2           0.5           0.5           0.5           0.5           0.5           0.5           0.6           0.7           etection V           0.2           0.5           no detection V           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V	e ater failure a swdel [ms]	40.4 40.4 829.5 829.5 829.5 829.5 1447.4 1447.4 1447.4 1447.4 1447.4 3273.8	76.8 mining heaters not film high heaters [ms] 1062.4 lailure	ed in any of the low heaters failure	98.2 <u>ese tria</u> <b>(ms)</b> 1070.9 1688.8 3515.2 <u>these trial</u> <b>(ms)</b> <b>(ms)</b>	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin mbcalure 1a.sin mbcalure 1a.sin mbcalure 1a.sin mbcalure 2a.sin mbcalure2a.sin mbcalure2a.sin mbcalure5a.sin mbcalure5a.sin mbcalure5a.sin mbcalure50.sin mbcalure602.sin mbcalure102.sin mbcalure102.sin mbcalure103.sin mbcalure103.sin mbcalure503.sin	39.035 RESULTS miits [kA*ka*s] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS miits [kA*ka*s] 28.414 28.973 29.412 RESULTS miits [kA*ka*s] 38.818 38.827 38.848 39.183	477.4 hot spot [K] 24.6. 24.7. 26.0: 26.0: 28.7. 28.7. 112. 97.40 hot spot [K] 123. 123. 127. hot spot [K] 289.1 290. 290. 290. 290. 297.2 297.2 297.4 297.4 297.4 299.4 299.4 299.2 297.2 297.4 297	11.776           resistive dev [Ohm]           16         0.0145           18         0.0156           9.9         0.0382           11         0.015811           1         0.0154           11         0.01542           12         0.0343           12         0.028495           resistive dev [Ohm]           15         0.0401           resistive dev [Ohm]           12         0.0284           resistive dev [Ohm]           12         0.0284           132         0.0381           14         0.2056           14         0.2056           17         0.2056           17         0.2056           17         0.2056	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.473 1.072 2.0665 91.443 3.803 3.803 3.803 3.803 91.443 10.708 10.708 10.553 9.146 time of max V [s] 2.799 2.8 2.794 2.5318
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.5           0.6           0.7           0.8           0.1           0.2           0.2           0.5           no detection           FAILURE 2: ht           detection V           0.1           0.2           0.5           no detection           FAILURE 3: ht           detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V	e aeter failure a swdel [ms]	40.4 4.8 kA (i 829.5 829.5 829.5 829.5 829.5 1447.4 1447.4 1447.4 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8 337.1 502.8 973 133.3 184.2 309.3	76.8 nner heaters not fin' high heaters (ms) high heaters (ms) lailure	ed in any of the Iow heaters failure	98.2 ese tria s [ms] 1070.9 1688.8 3515.2 s [ms] s [ms]	(s) inner heater do not fire als) inner heater do not fire S) inner heater do not fire	148.2 s (ms) s (ms)	mbcurrent506.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 1b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure50.sin mbfailure202.sin mbfailure202.sin mbfailure203.sin mbfailure203.sin	39.035 RESULTS mitts [kA*kA*s] 3.0325 3.0702 29.567 3.5946 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mitts [kA*kA*s] 38.818 38.818 38.848 39.183	477.4 hot spot [K] 24.6. 24.7. 120 26.1: 26.0. 117. 28. 28.7. 97.44 hot spot [K] 123.1 123.1 123.1 123.1 123.1 123.1 123.2 123.1 123.2	11/17/6           resistive dev [Ohm]           16         0.0148           18         0.0158           19         0.01581           11         0.00481           12         0.0144           13         0.01442           14         0.01481           15         0.028499           resistive dev [Ohm]         0.0337           15         0.0401           16         0.2054           12         0.2054           12         0.2054           13         0.2056           14         0.2056           17         0.3122	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 10.708 10.673 9.148 time of max V [s] 2.799 2.8 2.794 2.5318
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.2           0.2           0.5           0.5           0.5           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.9           0.9 </td <td>e eater failure a swdel [ms]</td> <td>40.4 829.5 829.7 8 827.8 8 8327.8 8 8 8 8 8 8 8 8 8 8 8 8 8</td> <td>76.8 mner heaters not fir high heaters [ms] 1062.4 lailure lailure 1680.3 lailure</td> <td>ed in any of th Tow heaters failure fa</td> <td>98.2 <u>ese tria</u> <u>s</u> [ms] 1070.9 1688.8 3515.2 <u>these tria</u> <u>s</u> [ms] <u>s</u> [ms] these trial</td> <td>(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire</td> <td>148.2 s [ms] s [ms]</td> <td>mbcurrent506.sin filename mbfailure 1a.sin mbfailure 15.sin mbfailure 20.sin mbfailure20.sin mbfailure20.sin mbfailure30.sin mbfailure30.sin mbfailure302.sin mbfailure302.sin mbfailure302.sin mbfailure303.sin mbfailure303.sin mbfailure303.sin</td> <td>39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5946 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 28.94 28.947 29.412 RESULTS mits [kA*kA*s] 38.818 38.827 38.848 39.483 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.485 39.4</td> <td>477.4 hot spot [K] 24.6. 24.7 26.0 117. 28. 28.7 112. 97.4 hot spot [K] 123. 1</td> <td>11/17/6           resistive dev [Ohm]           16         0.0148           18         0.0156           9         0.0382           10         0.01485           11         0.03647           12         0.0343           12         0.028495           15         0.0381           15         0.0381           15         0.0401           resistive dev [Ohm]         12           12         0.028495           15         0.0401           resistive dev [Ohm]         0.0381           12         0.0286           13         0.2056           14         0.2056           17         0.2056           17         0.2066           17         0.2066           17         0.2066</td> <td>8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3</td> <td>0.07871 time of max V [5] 1.3593 1.473 1.473 1.072 2.0655 91.443 3.803 3.8839 79.207 37.645 time of max V [5] 10.708 10.679 10.553 9.148 time of max V [5] 2.799 2.8 2.794 2.5318</td>	e eater failure a swdel [ms]	40.4 829.5 829.7 8 827.8 8 8327.8 8 8 8 8 8 8 8 8 8 8 8 8 8	76.8 mner heaters not fir high heaters [ms] 1062.4 lailure lailure 1680.3 lailure	ed in any of th Tow heaters failure fa	98.2 <u>ese tria</u> <u>s</u> [ms] 1070.9 1688.8 3515.2 <u>these tria</u> <u>s</u> [ms] <u>s</u> [ms] these trial	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire	148.2 s [ms] s [ms]	mbcurrent506.sin filename mbfailure 1a.sin mbfailure 15.sin mbfailure 20.sin mbfailure20.sin mbfailure20.sin mbfailure30.sin mbfailure30.sin mbfailure302.sin mbfailure302.sin mbfailure302.sin mbfailure303.sin mbfailure303.sin mbfailure303.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5946 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 28.94 28.947 29.412 RESULTS mits [kA*kA*s] 38.818 38.827 38.848 39.483 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.484 39.485 38.485 39.4	477.4 hot spot [K] 24.6. 24.7 26.0 117. 28. 28.7 112. 97.4 hot spot [K] 123. 1	11/17/6           resistive dev [Ohm]           16         0.0148           18         0.0156           9         0.0382           10         0.01485           11         0.03647           12         0.0343           12         0.028495           15         0.0381           15         0.0381           15         0.0401           resistive dev [Ohm]         12           12         0.028495           15         0.0401           resistive dev [Ohm]         0.0381           12         0.0286           13         0.2056           14         0.2056           17         0.2056           17         0.2066           17         0.2066           17         0.2066	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [5] 1.3593 1.473 1.473 1.072 2.0655 91.443 3.803 3.8839 79.207 37.645 time of max V [5] 10.708 10.679 10.553 9.148 time of max V [5] 2.799 2.8 2.794 2.5318
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.2           0.2           0.5           no detection           FAILURE 2: hr           detection V           0.1           0.2           0.5           no detection           V           0.1           0.2           0.5           no detection           V           0.1           0.2           0.5           no detection           V           0.5           no detection           FAILURE 4: hr           detection V	eater failure a swdel [ms] ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ;	40.4 829.5 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 3273.8 3273.8 3273.8 145.4A (ir 133.3 184.2 309.3 14.5 kA	76.8 nner heaters not fir high heaters (ms) lailure	ed in any of th Iow heaters failure fa	98.2 <u>ese tria</u> 1070.9 1688.8 3515.2 <u>hese tria</u> <b>s</b> [ms] <u>hese tria</u> <b>s</b> [ms]	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure50.sin mbfailure50.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5946 3.5946 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 38.818 38.828 38.848 39.183 RESULTS mits [kA*kA*s] 38.848 39.183	477.4 hot spot [K] 24.6. 24.7. 120 26.1. 26.0. 117. 28. 28.7. 112. 97.40 hot spot [K] 289.4 290. 297.5 hot spot [K]	19         1.1716           resistive dev [Ohm]           16         0.0145           18         0.01581           19         0.0382           10         0.015811           11         0.0382           12         0.0384           11         0.01442           12         0.028495           resistive dev [Ohm]         0.0377           15         0.0401           15         0.0401           12         0.2054           13         0.2054           14         0.2054           17         0.337           10         0.2054           11         0.2054           12         0.2054           13         0.2054           14         0.2054           17         0.3122           17         0.3202           17         0.3202           17         0.3202           17         0.3202           17         0.3202           18         0.2054           19         0.2054           10         0.2054      10         0.2054 <td>8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3</td> <td>0.07871 time of max V [s] 1.3593 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.8859 79.207 37.645 time of max V [s] 2.789 2.88 2.739 2.83 time of max V [s] 2.789 2.83 2.734 2.5318</td>	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.8859 79.207 37.645 time of max V [s] 2.789 2.88 2.739 2.83 time of max V [s] 2.789 2.83 2.734 2.5318
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           0.6           0.7           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.1           0.2           0.1	eater failure a swdel [ms] swdel [ms] c infinite eater failure a swdel [ms] swdel [ms] swdel [ms]	46.4 829.5 829.5 829.5 1447.4 1447.4 1447.4 3273.8 3273.8 11447.4 3273.8 3273.8 115.4 337.1 502.8 973 133.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 309.3 184.2 184	76.8 nner heaters not fir high heaters [ms] ialiure 1680.3 ialiure 1680.3 ialiure	ed in any of th Iow heaters failure	98.2 <u>ese tria</u> <b>s</b> [ms] 1070.9 1688.8 3515.2 <u>s</u> [ms] <u>s</u> [ms] <u>these trial</u> <b>s</b> [ms]	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 1b.sin mbfailure2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mb	39.035 RESULTS mits [kA*kA*] 3.0325 3.0702 29.567 3.5956 29.117 4.7163 4.6675 28.495 26.427 RESULTS mits [kA*kA*] 88.818 38.828 38.848 39.183 RESULTS mits [kA*kA*] 48.229	477.4 hot spot [K] 24.6. 24.7. 22. 26.1: 26.0. 117. 28.3 28.7. 127. hot spot [K] 28.9. 22.3 123.3 123.3 123.3 123.4 23.0 25.0	11.776           resistive dev (Ohm)           16         0.0148           19         0.0156           19         0.0156           10         0.01581           11         0.0382           12         0.01481           13         0.01448           14         0.01481           15         0.028499           resistive dev (Ohm)         0.0377           15         0.0381           15         0.0381           15         0.0401           resistive dev (Ohm)         12           12         0.2054           14         0.2054           17         0.2054           10         0.2054           11         0.2054           12         0.2054           13         0.42752	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.5503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 1.0.708 10.708 1.0.708 2.799 2.8 2.794 2.5318 time of max V [s] 1.5689
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.5           0.6           FAILURE 2: hr           detection V           0.1           0.2           0.5	e ater failure a swdel [ms]	40.4 829.5 827.8 837.1 13.3 163.8 164.2 82.6 82.6 82.6 82.7 8 8 8 8 8 8 8 8 8 8 8 8 8	76.8 nner heaters not fin' high heaters [ms] 1062.4 lailure	ed in any of the low heaters failure	98.2 <u>ese tria</u> s [ms] 1070.9 1688.8 3515.2 <u>these trial</u> s [ms] <u>these trial</u> s [ms]	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin mbcaliure 1a.sin mbcaliure 1a.sin mbcaliure 1a.sin mbcaliure 2b.sin mbcaliure2b.sin mbcaliure2b.sin mbcaliure5b.sin mbcaliure5b.sin mbcaliure5b.sin mbcaliure50.sin mbcaliure50.sin mbcaliure602.sin mbcaliure602.sin mbcaliure103.sin mbcaliure503.sin mbcaliure450.sin mbcaliure45b.sin	39.035 RESULTS mitts [kA*kA*s] 3.0325 3.0702 29.567 3.5946 29.117 4.7163 4.6675 28.485 26.427 RESULTS mitts [kA*kA*s] 38.818 38.827 38.848 38.848 38.848 39.183 RESULTS mitts [kA*kA*s] 48.229 48.236	477.4 hot spot [K] 24.6. 24.7. 120 26.1. 123. 28.7. 112. 97.40 hot spot [K] 123.4	11,1716           resistive dev [Ohm]           16         0.0145           18         0.0156           19         0.015811           11         0.0364           12         0.014457           13         0.014457           14         0.014427           15         0.028495           16         0.0379           17         0.0379           19         0.0381           107         0.0379           10         0.0381           15         0.0401           12         0.2056           17         0.2056           17         0.2056           17         0.2026           17         0.2026           17         0.2026           17         0.2026           10         0.42765           10         0.42765	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.473 10.085 91.443 3.803 3.803 3.803 91.443 10.708 10.708 10.708 10.708 10.553 9.148 time of max V [s] 2.799 2.8 2.794 2.5318 time of max V [s] 1.5685 1.5685
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           0.5           0.5           0.6           0.7           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5	e aeter failure a swdel [ms]	46.4 4 829.5 829.5 829.5 1447.4 1447.4 1447.4 1447.4 1247.3 8273.8 3273.8 3273.8 973 1447.4 145.4 4147.4 13273.8 973 133.3 154.2 309.3 144.2 415.4 411.5 164.2 309.3 164.2 309.3 164.2 309.3 164.2 309.3 164.2 164.9 124.2 165.2 16	76.8 76.8 76.8 76.8 76.8 76.8 76.8 76.8	ed in any of the low heaters failure	98.2 ese tria § [ms] 1070.9 1688.8 3515.2 these trial § [ms] these trial these trial (ms]	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin mbfallure 1a.sin mbfallure 1a.sin mbfallure 1b.sin mbfallure2b.sin mbfallure2b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5c.sin mbfallure5c.sin mbfallure5c.sin mbfallure5c.sin mbfallure602.sin mbfallure603.sin mbfallure603.sin mbfallure45b.sin mbfallure45c.sin	39.035 RESULTS mitts [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163 4.6675 28.455 26.427 RESULTS mitts [kA*kA*s] mitts [kA*kA*s] 48.229 48.229 48.239	477.4 hot spot [K] 24.6. 24.7. 120 26.1: 26.0. 117. 28. 287. 112. 97.4 hot spot [K] 289.1 290. 290. 290. 290. 297.3 hot spot [K] 663. 663. 663. 663. 663.	11         11           resistive dev (Ohm)         0.0148           16         0.0148           19         0.01581           11         0.0382           12         0.01481           11         0.01681           12         0.028498           resistive dev (Ohm)         0.0337           12         0.0384           15         0.0401           resistive dev (Ohm)         12           12         0.2054           13         0.2056           14         0.2056           14         0.2056           15         0.2061           16         0.42752           16         0.42752           16         0.42752           16         0.42752	max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 2.799 2.8 2.794 2.5318 time of max V [s] 1.5682 1.5682 1.5682
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           no detection V	e eater failure a swdel [ms]	46.4 (1) 829.5 (2) 829.5 (2) 827.5 (2) 8	78.8 78.8 78.8 78.8 78.8 78.8 78.8 78.8	ed in any of th Iow heaters failure	98.2 ese tria [ms] 1070.9 1688.8 3515.2 these trial s [ms] these trial these trial	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin mbcalure 10.sin mbcalure 10.sin mbcalure 10.sin mbcalure 20.sin mbcalure 45.sin mbcalure 45.sin	39.035 RESULTS milts [kA*kA*s] 3.0325 3.0702 29.5475 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS milts [kA*kA*s] 38.818 38.827 38.848 39.183 39.183 48.829 4	477.4 hot spot [K] 24.6. 24.7. 26.0. 26.0. 27.7. 28.7. 28.7. 28.7. 112. 97.40 hot spot [K] 123. 124. 125.	11         1.1716           resistive dev [Ohm]         0.0145           16         0.0145           17         0.0156           19         0.0156           10         0.0156           11         0.015811           11         0.01541           12         0.0343           12         0.028495           resistive dev [Ohm]         10           12         0.0381           15         0.0401           resistive dev [Ohm]         12           12         0.2056           13         0.42765           14         0.42765           15         0.42765           14         0.42765           15         0.333           14         0.42765	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.473 1.072 2.0665 91.443 3.803 3.803 3.803 91.443 10.708 10.708 10.708 10.503 9.148 time of max V [s] 2.799 2.8 2.794 2.5318 time of max V [s] 1.5685
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.2           0.5           no detection           FAILURE 2: hr           detection V           0.1           0.2           0.5           no detection           V           0.1           0.2           0.5           no detection           V           0.1           0.2           0.5           no detection           V           0.1           0.2           0.5           no detection	e atter failure a swdel [ms] infinite eater failure a swdel [ms] swdel [ms] infinite eater failure a swdel [ms] infinite eater failure a swdel [ms]	46.4 (18 KA (i 829.5 829.5 829.5 829.5 1447.4 147.4 147.4 147.4 147.4 147.4 147.4 147.4 147.4 147.4	76.8 nner heaters not fin high heaters [ms] 1062.4 iailure iai	ed in any of th Iow heaters failure	98.2 ese tria 5 [ms] 1070.9 1688.8 3515.2 5 [ms] 5 [ms] these trial 6 [ms]	(s) inner heater do not fire als) inner heater do not fire (s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin mbfallure 1a.sin mbfallure 1a.sin mbfallure 1a.sin mbfallure 2b.sin mbfallure2b.sin mbfallure2b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5c.sin mbfallure6c.sin mbfallure6c.sin mbfallure6c2.sin mbfallure6c2.sin mbfallure6c3.sin mbfallure6c3.sin mbfallure45b.sin mbfallure45b.sin mbfallure45b.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5946 3.5956 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 38.818 38.827 mits [kA*kA*s] 48.239 48.2	477.4 hot spot [K] 24.6. 24.7. 120 26.1. 26.0. 117. 28. 28.7. 112. 97.44 hot spot [K] 289.4 290. 297.4 hot spot [K] 663.6 663.6 663.6 663.6 663.6 663.6 664.6 665.6 65	19         1.1716           resistive dev [Ohm]           16         0.0148           19         0.0382           16         0.01481           11         0.0382           12         0.01481           13         0.0382           14         0.01481           15         0.028495           16         0.0337           17         0.0337           19         0.0388           15         0.0401           16         0.42054           11         0.2054           12         0.2054           13         0.2054           14         0.2054           15         0.4011           16         0.42765           16         0.42765           11         0.42433           13         0.34386 <td>8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3</td> <td>0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 1.0708 10.673 9.148 time of max V [s] 2.799 2.8 2.794 2.5318 time of max V [s] 1.5685 1.5682 1.4291</td>	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 1.0708 10.673 9.148 time of max V [s] 2.799 2.8 2.794 2.5318 time of max V [s] 1.5685 1.5682 1.4291
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           0.6           0.7           0.1           0.2           0.5           0.6           0.7           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.5           no detection V           0.1           0.2           0.1           0.2           0.1           0.2           0.1           0.2           0.1           0.2           0.1           0.2           0.1      0.2      <	e ater failure a swdel [ms] infinite eater failure a swdel [ms] swdel [ms] infinite eater failure a swdel [ms] infinite eater failure a swdel [ms]	46.4 (1) 40.4 (	76.8 nner heaters not fin' high heaters [ms] 1062.4 lailure	ed in any of the low heaters failure f	98.2 ese tria [ms] 1070.9 1688.8 3515.2 these tri [ms] these trial these trial these trial	(s) inner heater do not fire (als) inner heater do not fire (als) inner heater do not fire (als) (	148.2 s [ms] s [ms] s [ms]	mbcurrent506.sin filename mbfallure 1a.sin mbfallure 1b.sin mbfallure 2b.sin mbfallure2b.sin mbfallure2b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5c.sin mbfallure6c.sin mbfallure602.sin mbfallure602.sin mbfallure603.sin mbfallure503.sin mbfallure503.sin mbfallure503.sin mbfallure503.sin mbfallure503.sin mbfallure45b.sin mbfallure45b.sin mbfallure45b.sin	39.035 RESULTS milts [kA*ka*s] 3.0702 29.567 3.5956 29.107 4.7163 4.6675 28.485 26.427 RESULTS milts [kA*ka*s] 8.814 38.818 38.827 38.848 39.183 38.827 38.848 39.183 39.848 39.183 39.848 39.8487 39.8487 48.229 48.874 RESULTS	477.4 hot spot [K] 24.6. 24.7. 26.0. 117. 28.7 28.7 122. 97.4 hot spot [K] 123. 124. 125. 125. 125. 125. 125. 125. 125. 125. 125. 125. 125. 125. 127. hot spot [K] 663. 66	19         1.1716           resistive dev [Ohm]           16         0.0145           19         0.0156           19         0.0156           10         0.015811           11         0.015811           12         0.014457           14         0.016441           11         0.01442           12         0.028499           resistive dev [Ohm]         0.0378           15         0.0401           resistive dev [Ohm]         12           12         0.2056           13         0.34386           14         0.42762           15         0.42762           16         0.42763           13         0.34386	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1.473 1.473 1.473 1.472 2.065 91.443 3.803 3.803 3.803 9.143 time of max V [s] 10.708 10.708 10.533 9.148 time of max V [s] 2.794 2.5318 time of max V [s] 1.5685 1.5682 1.4291
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.2           0.5           no detection V           detection V           detection V           0.5           no detection V	e eater failure a swdel [ms] infinite eater failure a swdel [ms] eater failure a swdel [ms] infinite eater failure a swdel [ms] infinite eater failure a swdel [ms] swdel [ms] swdel [ms] swdel [ms] swdel [ms]	46.4 (18829.5 829.5 829.5 829.5 829.5 829.5 1447.4	76.8 nner heaters not fin high heaters [ms] 1062.4 lailure lai	ed in any of the low heaters failure f	98.2 <u>ese trial</u> 1070.9 1688.8 3515.2 <u>these trial</u> <b>s</b> [ms] <u>these trial</u> <b>s</b> [ms] <u>ese trial</u> <b>s</b> [ms]	(s) inner heater do not fire als) inner heater do not fire s) inner heater do not fire als) inner heater do not fire	148.2 s (ms) s (ms) s (ms) s (ms) s (ms)	mbcurrent506.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure5b.sin mbfailure50.sin mbfailure50.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure20.sin mbfailure450.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin	39.035 RESULTS mitts [kA*kA*s] 3.0325 3.0702 29.567 3.5946 29.117 4.7163 4.6675 28.485 26.427 RESULTS mitts [kA*kA*s] 38.818 38.827 38.848 39.183 RESULTS mitts [kA*kA*s] 48.229 48.239	477.4 hot spot [K] 24.6. 24.7. 120 26.1. 26.0. 117. 28.7 28.7 28.7 112. 97.40 hot spot [K] 289.9 290. 297.5 hot spot [K] 663. 663. 663. 663. 663. 663. 664.	19         1.1716           resistive dev [Ohm]           16         0.0145           18         0.01581           19         0.01581           11         0.0382           12         0.0382           13         0.0382           14         0.015811           1         0.0382           12         0.028495           13         0.0382           14         0.0375           15         0.0401           12         0.2054           13         0.2054           14         0.2054           15         0.0401           12         0.2054           13         0.2054           14         0.42765           15         0.42765           16         0.42765           13         0.34386           13         0.34386           14         0.42765           15         0.34386           16         0.42765           17         0.34386           13         0.34386	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1.473 1.9772 2.0665 91.443 3.803 3.8859 79.207 37.645 time of max V [s] 1.0708 10.619 2.799 2.8 2.794 2.5318 time of max V [s] 1.5685 1.5685 1.5685 1.4291
FAILURE 1: ht           detection V           0.1           0.1           0.1           0.1           0.2           0.5           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           0.6           0.7           0.8           0.9           0.1           0.2           0.5           no detection V           0.1           0.2           0.5	eater failure a swdel [ms] infinite eater failure a swdel [ms] infinite eater failure a swdel [ms] infinite eater failure a swdel [ms] swdel [ms]	46.4 (1) 829.5 (2) 829.5 (2) 829.5 (2) 829.5 (2) 829.5 (2) 829.5 (2) 829.5 (2) 829.5 (2) 829.5 (2) 827.3 (2) 8	76.8 mner heaters not fir high heaters [ms] 1062.4 iailure iailure 1680.3 iailure	ed in any of the low heaters failure f	98.2 <u>ese trial</u> [ms] 1070.9 1688.8 3515.2 <u>these trial</u> <u>s [ms]</u> <u>these trial</u> <u>these trial</u>	(s) inner heater do not fire als) inner heater do not fire als) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms] s [ms] s [ms]	mbcurrent506.sin mbfallure 1a.sin mbfallure 1a.sin mbfallure 1b.sin mbfallure 2b.sin mbfallure2b.sin mbfallure2b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5c.sin mbfallure5c.sin mbfallure5c.sin mbfallure5c.sin mbfallure602.sin mbfallure603.sin mbfallure603.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin	39.035 RESULTS mits [kA*kA*s] 3.0325 3.0702 29.567 3.5995 29.117 4.7163 4.6675 28.485 26.427 RESULTS mits [kA*kA*s] 88.878 RESULTS mits [kA*kA*s] 48.229 48.239 48.339 48.348 58.	477.4 hot spot [K] 24.6. 24.7. 22.6.1. 26.0. 120. 26.0. 120. 26.0. 26.0. 26.0. 27. 28.0. 28.0. 28.0. 29.0. 20.0	11/17/6           resistive dev [Ohm]           16         0.0145           18         0.0156           19         0.0384           10         0.01457           11         0.03647           12         0.0343           12         0.028495           14         0.01581           15         0.0381           16         0.028495           17         0.0378           10         0.0381           15         0.0401           16         0.02086           17         0.0374           18         0.0381           19         0.0381           10         0.2056           17         0.2056           17         0.2056           17         0.2056           17         0.1322           10         0.42752           16         0.42752           13         0.34386           13         0.34386           14         0.42433           13         0.34386           14         0.51306	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1.072 2.0655 91.443 3.803 3.8839 79.207 37.645 time of max V [s] 1.079 2.799 2.8 2.794 2.5318 time of max V [s] 1.5689 1.5685 1.5685 1.4291 time of max V [s] 1.1614
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           no detection V           0.1           0.2           0.5	e eater failure a swdei [ms] 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 5 5 5 6 6 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2	46.4 (1) 46.4 (1) 4829.5 (2) 429.5 (2) 429.5 (2) 429.5 (2) 429.5 (2) 429.5 (2) 429.5 (2) 429.5 (2) 447.4 (2) 429.5 (2) 447.4 (2) 429.5 (2) 432.5 (2) 4	76.8 mner heaters not fin' high heaters [ms] 1062.4 lailure	ed in any of the low heaters failure	98.2 <u>ese trial</u> 1070.9 1688.8 3515.2 <u>these trial</u> <u>s [ms]</u> <u>ese trial</u> <u>s [ms]</u>	(s) inner heater do not fire als) inner heater do not fire als) inner heater do not fire als) inner heater do not fire	148.2 s (ms) s (ms) s (ms) s (ms)	mbcurrent506.sin mbcaurent506.sin mbfailure 1a.sin mbfailure 1a.sin mbfailure 2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure2b.sin mbfailure5b.sin mbfailure5b.sin mbfailure50.sin mbfailure50.sin mbfailure602.sin mbfailure602.sin mbfailure603.sin mbfailure45a.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin mbfailure45b.sin	39.035 RESULTS mitts [kA*kA*s] 3.0325 3.0702 29.567 3.5946 29.117 4.7163 4.6675 28.485 26.427 RESULTS mitts [kA*kA*s] 38.827 38.848 39.183 RESULTS mitts [kA*kA*s] mitts [kA*kA*s] 48.229 48.230 48.250	477.4 hot spot [K] 24.6. 24.7. 120 26.1. 123. 1	11,1716           resistive dev [Ohm]           16         0.0145           18         0.0156           19         0.015811           11         0.0384           12         0.014857           13         0.014457           14         0.014811           1         0.038495           12         0.028495           13         0.0381           14         0.0375           15         0.0401           16         0.02066           17         0.0375           18         0.2056           17         0.0375           18         0.2056           19         0.02066           10         0.42765           11         0.42765           12         0.2056           13         0.34386           14         0.42765           15         0.34366           14         0.42765           15         0.34386           13         0.343866           14         0.51306           15         0.51306	8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3593 1.473 1.473 10.08 1.9772 2.0665 91.443 3.803 3.883 91.443 10.708 10.708 10.708 10.708 10.708 10.553 9.148 time of max V [s] 2.799 2.8 2.794 2.5318 time of max V [s] 1.5685 1.5682 1.4291 time of max V [s] 1.1614
FAILURE 1: hr           detection V           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.1           0.2           0.5           0.6           0.7           0.1           0.2           0.5           no detection V           0.1           0.2           0.5	eater failure a swdel [ms] swdel [ms] sinfinite eater failure a swdel [ms] infinite eater failure a swdel [ms] infinite eater failure a swdel [ms]	46.4 (1) 40.4 (	76.8 nner heaters not firi high heaters [ms] hig	ed in any of the low heaters failure	98.2 <u>esse trial</u> 1070.9 1688.8 3515.2 <u>these trial</u> <u>s [ms]</u> <u>these trial</u> <u>these trial</u>	(s) inner heater do not fire als) inner heater do not fire (s) inner heater do not fire als) inner heater do not fire	148.2 s [ms] s [ms] s [ms] s [ms]	mbcurrent506.sin mbfallure 1a.sin mbfallure 1a.sin mbfallure 1a.sin mbfallure 2b.sin mbfallure2b.sin mbfallure2b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure5b.sin mbfallure202.sin mbfallure202.sin mbfallure203.sin mbfallure45a.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin mbfallure45s.sin	39.035 RESULTS mitts [kA*kA*s] 3.0325 3.0702 29.567 3.5945 3.5956 29.117 4.7163 4.6675 28.455 26.427 RESULTS mitts [kA*kA*s] 48.229 48.239 52.811 52	477.4 hot spot [K] 24.6. 24.7 20.6.1; 26.0. 112. 26.0. 123. 287.4 hot spot [K] 289.4 290.4 200.4 20.	11         11           resistive dev (Ohm)         0.0148           16         0.0148           19         0.01581           11         0.0382           12         0.01481           11         0.016811           12         0.028496           12         0.028492           resistive dev (Ohm)         0.037           13         0.0381           14         0.0376           15         0.0401           resistive dev (Ohm)           12         0.2054           13         0.2057           14         0.2054           15         0.2064           16         0.42752           17         0.3338           13         0.34386           14         0.42433           15         0.34386           16         0.42752           17         0.34386           18         0.51306           18         0.51306           18         0.51306           19         0.51306           10         0.51306	max Vmag [V] 8.3 8.3 8.3 8.3 8.3 8.3 8.3 8.3	0.07871 time of max V [s] 1.3503 1.473 1.00.8 1.9772 2.0665 91.443 3.803 3.885 79.207 37.645 time of max V [s] 1.0708 10.679 2.794 2.794 2.794 2.794 2.5318 time of max V [s] 1.5682 1.5682 1.5682 1.5682 1.4291 time of max V [s] 1.5683 1.5682 1.4291 1.5682 1.5682 1.4291 1.5682

# **APPENDIX B: HEATER STUDY DATA**

Template	Detection [V]	Validation [ms]	swdel [ms]	High heaters [ms]	Low heaters [ms]	Inner heaters [ms]	Hot spot [K]	Vmax [V]	t of Vmag [s]	resdev [Ohm]	miits [kA*kA*s]	idot @tinner [A/s]	filename
Carles	0.1			54.4	74.4	104.4	266.00		0.056102	1 1200	25 502	C005 7	mh tain
Series	0.1	5	24.1	54.1	74.1	134.1	366.99	8.3	0.056192	1.1308	35.562	-6885./	mb1.sin
Series	0.1	5	24.1	54.1	74.1	174.1	378.93	8.3	0.056192	1.1444	36.016	-16873	mb2.sin
Series	0.1	5	24.1	54.1	84.1	144.1	375.35	8.3	0.056192	1.1353	35.891	-8284.2	mb3.sin
Series	0.1	5	24.1	54.1	84.1	184.1	385.06	8.3	0.056192	1.145	36.227	-18265	mD4.SIN
Series	0.1	5	24.1	59.1	79.1	139.1	386.83	8.3	0.061171	1.1308	36.288	-6888.4	mb5.sin
Series	0.1	5	24.1	59.1	79.1	179.1	399.43	8.3	0.061171	1.1453	36.709	-16872	mbb.sin
Series	0.1	5	24.1	59.1	89.1	149.1	395.66	8.3	0.061171	1.1348	36.584	-8232.0	mb7.SIN
Series	0.1	-	24.1	59.1	09.1	109.1	405.92	0.3	0.001171	1.1443	30.92	-16304	nibo.sin
Series	0.1	10	29.1	59.1	79.1	139.1	386.86	8.3	0.061176	1.1309	36.289	-6889.2	mb9.sin
Series	0.1	10	29.1	59.1	79.1	179.1	399.47	8.3	0.061176	1.1454	36.71	-16875	mb10.sin
Series	0.1	10	29.1	59.1	89.1	149.1	395.7	8.3	0.061176	1.1349	36.585	-8223.8	mb11.sin
Series	0.1	10	29.1	59.1	89.1	189.1	405.95	8.3	0.061176	1.1446	36.921	-1836/	mb12.sin
Series	0.1	10	29.1	64.1	84.1	144.1	407.78	8.3	0.066139	1.1302	36.981	-6944.6	mb13.sin
Series	0.1	10	29.1	64.1	84.1	184.1	421.09	8.3	0.066139	1.1447	37.402	-16883	mb14.sin
Series	0.1	10	29.1	64.1	94.1	154.1	417.11	8.3	0.066139	1.1342	37.277	-8237.4	mb15.sin
Series	0.1	10	29.1	64.1	94.1	194.1	427.93	8.3	0.066139	1.1439	37.613	-18286	mD16.SIN
Series	0.2	5	i 31.1	61.1	81.1	141.1	395.12	8.3	0.063164	1.1307	36.566	-6890.6	mb17.sin
Series	0.2	5	i 31.1	61.1	81.1	181.1	407.9	8.3	0.063164	1.1448	36.985	-16891	mb18.sin
Series	0.2	5	i 31.1	61.1	91.1	151.1	404.15	8.3	0.063164	1.1346	36.863	-8300	mb19.sin
Series	0.2	5	i 31.1	61.1	91.1	191.1	414.63	8.3	0.063164	1.1443	37.198	-18282	mb20.sin
Series	0.2	5	i 31.1	66.1	86.1	146.1	416.49	8.3	0.068129	1.1299	37.258	-6901.1	mb21.sin
Series	0.2	5	i 31.1	66.1	86.1	186.1	430.08	8.3	0.068129	1.1444	37.678	-16888	mb22.sin
Series	0.2	5	i 31.1	66.1	96.1	156.1	426.03	8.3	0.068129	1.1339	37.554	-8239.5	mb23.sin
Series	0.2	5	i 31.1	66.1	96.1	196.1	437.09	8.3	0.068129	1.1436	37.89	-184055	mb24.sin
Series	0.2	5	i 31.1	61.1	81.1	121.1	386.75	8.3	0.063164	1.1268	36.285	-5196.7	mb50.sin
Series	0.2	5	i 31.1	61.1	91.1	121.1	391.31	8.3	0.063164	1.1264	36.439	-4761.4	mb51.sin
Series	0.2	5	i 31.1	61.1	91.1	141.1	399.83	8.3	0.063164	1.1294	36.722	-6926.5	mb52.sin
Series	0.2	5	i 31.1	61.1	91.1	181.1	412.75	8.3	0.036164	1.1416	37.139	-14886	mb53.sin
Series	0.2	5	i 31.1	66.1	81.1	121.1	399.35	8.3	0.068129	1.1262	36.706	-4985.5	mb54.sin
Series	0.2	5	i 31.1	66.1	81.1	141.1	408.77	8.3	0.068129	1.1304	37.013	-6431.2	mb55.sin
Series	0.2	5	i 31.1	66.1	81.1	181.1	422.4	8.3	0.068129	1.1444	37.442	-15692	mb56.sin
Series	0.2	5	i 31.1	66.1	91.1	121.1	408.97	8.3	0.068129	1.1175	37.019	-4449.9	mb57.sin
Series	0.2	5	i 31.1	66.1	91.1	141.1	418.87	8.3	0.068129	1.1261	37.332	-6395.4	mb58.sin
Series	0.2	5	31.1	66.1	91.1	181.1	433.17	8.3	0.068129	1.1342	37.772	-13569	mb59.sin
Series	0.2	5	i 31.1	71.1	81.1	121.1	413.86	8.3	0.073108	1.1298	37.174	-4658.7	mb60.sin
Series	0.2	5	31.1	71.1	81.1	141.1	424.71	8.3	0.073108	1.1353	37.513	-6448.4	mb61.sin
Series	0.2	5	i 31.1	71.1	81.1	181.1	439.3	8.3	0.073108	1.1487	37.956	-14458	mb62.sin
Series	0.2	5	i 31.1	71.1	91.1	121.1	423.16	8.3	0.073108	1.1217	37.466	-4120.4	mb63.sin
Series	0.2	5	i 31.1	71.1	91.1	141.1	434.77	8.3	0.073108	1.1287	37.82	-6205.7	mb64.sin
Series	0.2	5	i 31.1	71.1	91.1	181.1	450.12	8.3	0.073108	1.1376	38.274	-12514	mb65.sin
Series	0.2	10	36.1	66.1	86.1	146.1	416.53	8.3	0.068131	1.13	37.259	-6902	mb33.sin
Sorios	0.5		. 16 /	76.4	96.4	156 /	/63.70	8 3	0.078386	1 1 2 7	38 665	-6008 3	mb25 sin
Sorios	0.5		46.4	76.4	96.4	196./	1 178.95	8.3	0.078386	1 1/19	39.086	-0330.0	mb26.sin
Series	0.5			70.4	106.4	190	470.55	0.0	0.078380	1 1 2 1 2	39.000	-17000	mb27.sin
Sorios	0.5		46.4	76.4	106.4	206.4	/86.78	8.3	0.078386	1 1 4 0 9	30.302	-0505.7	mb28 sin
Series	0.5			91.4	100.4	200	400.70	0.0	0.070300	1 1 1 2 7 2	35.257	-10410	mb20.sin
Sorios	0.5		46.4	81.4	101.4	201.4	505.50	8.3	0.083362	1 1/16	30.70	-160/0	mb20.sin
Sorios	0.5		46.4	81.4	111.4	171 /	500.78	8.3	0.003362	1 1311	30 668	-10343	mb31 sin
Sorios	0.5		46.4	81.4	111.4	211.4	513.0	8.3	0.083362	1 1 / 1 /	40.005	-1834/	mb32 sin
Series	0.5	10	9 40.4 1 51.4	81.4	101.4	161.4	/89.62	0.0	0.083364	1 1 2 7 4	40.003	-6013 7	mb34 sin
Selles	0.5		51.4	01.4	101.4	101.4	405.02	0.3	0.000004	1.12/4	35.374	-0913.7	11034.311
Single	0.1	5	24.1	54.1	74.1	134.1	347.45	-235.67	0.0241	1.0407	34.873	-9017.2	mb1s.sin
Single	0.1	5	i 24.1	59.1	89.1	189.1	386.62	-235.67	0.0241	1.0479	36.281	-20345	mb8s.sin
Single	0.1	10	29.1	59.1	79.1	139.1	366.05	-235.67	0.0291	1.0396	35.561	-8833.3	mb9s.sin
Single	0.1	10	29.1	64.1	94.1	194.1	407.59	-235.67	0.0291	1.047	36.975	-20354	mb16s.sin
Single	0.2	5	i 31.1	61.1	81.1	141.1	373.46	-236.14	0.0311	1.0405	35.824	-8834.2	mb17s.sin
Single	0.2	5	i 31.1	66.1	96.1	196.1	416.28	-236.14	0.0311	1.0468	37.251	-20359	mb24s.sin
Single	0.5	5	i 46.4	76.4	96.4	156.4	439.1	-235.67	0.0464	1.0369	37.95	-8914.7	mb25s.sin
Single	0.5	5	46.4	81.4	111.4	211.4	489.3	-235.67	0.0464	1.0436	39.365	-20403	mb32s.sin

PARAMETER STUDY AT 11796 A (quench velocity = 1500 cm/sec)

# APPENDIX C: DATA FOR APERTURE QUENCH ASYMMETRIES

Heater dela	y aperti	APERTU	Detection RF 1 [ms]	on at .2\	APERTU	s validati RF 2 (ms)	on perio	bd	Maximum inte	ramagnet volta	aes occurina i	(not necessaril	v at the same t	time)		
filename	ewdol	high field	low field	inner	high field	low field	inner	MIITS	unner outer1	unner inner1	lower inner1	lower outer1	unner outer?	unner inner?	lower inner?	lower outer?
mbh1 sin	31 1	61 1	81 1	121 1	1 66 1	81 1	121 1	36 439	287 3	_265.41	-265 41	305 30	234.05	-265 41	-265.41	235 50
mhh2 sin	31.1	66 1	81.1	121.1	1 61.1	81.1	121.1	36.439	207.0	-265.47	-265.47	230.24	300.05	-265.47	-265.47	301.58
mbh2 ain	21.1	64.4	01.1	121.	1 64.4	01.1	121.1	35,002	221.40	203.42	-203.42	233.24	259.29	-203.42	-203.42	250 0
1110113.5111	51.1	01.1	01.1	121.	01.1	01.1	121.1	33.333	240.50	-207.02	=207.02	203.34	200.00	-207.02	=237.02	200.0
mbh4.sin	31.1	61.1	81.1	121.1	1 71.1	81.1	121.1	36.674	329.49	-255.09	-255.09	348.29	170.81	-255.09	-255.09	172.43
mbh5.sin	31.1	71.1	81.1	121.1	1 61.1	81.1	121.1	36.671	167.72	-257.67	-257.67	176.59	342.73	-257.67	-257.67	344.29
mbh3.sin	31.1	61.1	81.1	121.1	1 61.1	81.1	121.1	35.993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259.9
mbh20.sin	31.1	61.1	81.1	121.1	1 failure	81.1	121.1	39.26	764.65	-166	-166	795.41	-452.99	-166	-166	-452.99
mbh21.sin	31.1	failure	81.1	121.1	1 61.1	81.1	121.1	39.12	-377.33	-173.06	-173.06	-497.02	782.64	-173.06	-173.06	784.49
mbh3 sin	31.1	61.1	81.1	121.1	61.1	81.1	121.1	35,993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259.9
mbh6.sin	31.1	61.1	71.1	121.1	1 61.1	91.1	121.1	36.039	301.06	-265.15	-265.15	321.34	218.76	-265.15	-265.15	220.22
mbh7.sin	31.1	61.1	91.1	121.1	1 61.1	71.1	121.1	36.045	202.58	-265	-265	224.3	316.21	-265	-265	317.67
mbh8.sin	31.1	61.1	91.1	121.1	1 61.1	91.1	121.1	36.439	249.79	-265.23	-265.23	273.29	268.55	-265.23	-265.23	270.04
mbh9 sin	31.1	61.1	81.1	121.1	1 61.1	91.1	121.1	36,262	273.13	-266.03	-266.03	294.94	247.59	-266.03	-266.03	249.17
mhh10 sin	31.1	61.1	91.1	121 1	1 61 1	81.1	121.1	36 264	230.25	-265.98	-265.98	252 57	290.1	-265.98	-265.98	291.60
mbh8 sin	31.1	61.1	91.1	121 1	1 61 1	91.1	121.1	36 439	249 79	-265.23	-265 23	273.29	268 55	-265 23	-265 23	270.04
	• • • •		•			•										
mbh22.sin	31.1	61.1	81.1	121.1	1 61.1	failure	121.1	36.799	353.88	-247.88	-247.88	372.67	132.04	-247.88	-247.88	133.61
mbh23.sin	31.1	61.1	failure	121.1	1 61.1	81.1	121.1	36.815	114.13	-247.35	-247.35	134.35	369.99	-247.35	-247.35	371.57
mbh3.sin	31.1	61.1	81.1	121.1	1 61.1	81.1	121.1	35.993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259.9
mhhdd ain	24.4	61.1	01.1	424 4	. 61.1	01.1	464 4	26.246	270.02	256.04	256.04	207.24	201.0	202.07	202.07	202.42
IIIDIIII.SIII	31.1	01.1	01.1	121.	01.1	01.1	101.1	30.240	279.92	-200.94	-200.94	297.24	291.9	-323.97	-323.97	293.43
mbn12.sin	31.1	01.1	81.1	161.1	1 61.1	81.1	121.1	30.240	2/9.92	-323.97	-323.97	297.24	291.9	-256.94	-256.94	293.43
mbh3.sin	31.1	61.1	81.1	121.1	<b>i</b> 61.1	81.1	121.1	35.993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259.9
mbh13.sin	31.1	61.1	81.1	121.1	<b>1</b> 61.1	81.1	91.1	35.607	206.08	-261.88	-261.88	225.53	220.73	-175.02	-175.02	222.2
mbh14.sin	31.1	61.1	81.1	91.1	<b>1</b> 61.1	81.1	121.1	35.606	206.15	-175.1	-175.1	225.63	220.79	-261.95	-261.95	222.26
mbh3.sin	31.1	61.1	81.1	121.1	<b>1</b> 61.1	81.1	121.1	35.993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259.9
mbh24 cin	21.1	61.1	01.1	121 -	61 1	91.1	failuro	26 540	225.09	252 71	252 71	244 17	220 61	420.45	420.45	240.10
mbh25.cin	21.1	61.1	01.1	failuro	61.1	01.1	121 1	26 549	325.50	420.45	-200.71	344.17	220.01	-420.43	-420.43	340.10
mbh2 ain	21.1	61.1	01.1	424 4	01.1 • 61.1	01.1	424.4	30.343	323.90	-420.43	-420.43	0000	250.01	-200.71	-200.71	250.0
1110113.5111	31.1	01.1	01.1	121.	01.1	01.1	121.1	35.993	240.90	-257.02	-257.02	203.34	200.00	-257.02	-257.02	209.5
mbh26.sin	31.1	61.1	81.1	121.1	1 failure	failure	failure	41.086	1216.7	-102.67	-102.67	1256	-773.05	-360.59	-360.59	-773.05
mbh27.sin	31.1	failure	failure	failure	61.1	81.1	121.1	40.813	-632.51	-364.16	-364.16	-780.7	1182.7	-113.2	-113.2	1184.1
mbh3.sin	31.1	61.1	81.1	121.1	1 61.1	81.1	121.1	35.993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259.9
mhh28 sin	31.1	61 1	failure	failure	failure	81.1	121 1	41 012	765.93	-360.34	-360.34	806.85	-332 7	-104 65	-104 65	-332 7
mhh29 sin	31.1	failure	81 1	121 1	1 61 1	failure	failure	40.67	-219 28	-118.07	-118.07	-349.07	747 45	-365.06	-365.06	748 94
mbh3 sin	31.1	61 1	81.1	121 1	1 61.1	81 1	121 1	35 993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259 0
mono.ani	01.1	01.1	01.1	141.	. 01.1	01.1	141.1	00.000	2-10.30	-201.02	-201.02	200.04	200.00	-201.02	-201.02	200.0
mbh30.sin	31.1	61.1	failure	121.1	1 failure	81.1	failure	41.013	765.93	-104.65	-104.65	806.85	-332.7	-360.34	-360.34	-332.7
mbh31.sin	31.1	failure	81.1	failure	61.1	failure	81.1	40.67	-219.3	-365.1	-365.1	-349.1	747.53	-118.07	-118.07	749.02
mbh3.sin	31.1	61.1	81.1	121.1	<b>1</b> 61.1	81.1	121.1	35.993	246.96	-257.02	-257.02	263.54	258.38	-257.02	-257.02	259.9